HIGH AND LOW TENSION SWITCH-GEAR DESIGN

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PREFACE

THE following pages contain the result of researches made with the object of obtaining accurate data as to the effects caused by opening and closing the circuits with various types of electrical apparatus.

The major portion of this contribution is expressly intended as an introduction to the main elements of design, which will be more abstracted by further publications on the individual subjects involved.

The multiplicity of designs and the mathematical treatment of each subject could not be dealt with in one publication, as the latter would not only burden the memory unnecessarily, but would likewise be of such mammoth dimensions as to be beyond the reach of those whose interest in the subject is primarily of a superficial character. The subject is treated in such manner that the essentials may be easily understood by those interested in this class of apparatus.

It is hoped that the great body of " engineers " and " artisans " in all departments of electrical engineering practice will find these pages an invaluable aid in their efforts to acquire a better knowledge of the most important portion of an electrical equipment.

Historically, switchgear has not developed correspondingly with the development of electrical transmissions, it being only lately realized that its function is one, if not the most important, factor in the success of such installations, and it is regrettable to note the absence of proper provision to

ensure its efficient working. It is hoped that the diagrams in this book will be of service to designers.

The oscillograph records produced are the result of patient perseverance; were obtained only with great difficulty and expense; up to the present are unique, and believed to be the first published records of their kind. It is essential that purchasers and manufacturers should combine towards the production of efficient switchgear and support financially any efforts towards this end.

A. G. COLLIS.

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CHAPTER I

INTRODUCTORY—SWITCHGEAR FOR HIGH PRESSURE SERVICE—EXAMPLES—REPORT OF FAILURES—QUESTION OF SPACE—SECTIONALIZING—ISOLATION—LEAKAGE—GENERAL PRINCIPLES—IRONCLAD TWO-PHASE EQUIPMENT—IRONCLAD THREE-PHASE EQUIPMENT—INTRODUCTION OF H.T. SWITCHBOARD DESIGN—SWITCHBOARD STRUCTURES—MOULDED STONE—REINFORCED CONCRETE—IRONCLAD CUBICLE STRUCTURE—ILLUSTRATION OF H.T. FEEDER AND GENERATOR PANELS—REMOTE CONTROL GEAR—PLUG CONNECTIONS—MAGNETIC STRAINS—RING FORM OF BUSBAR DESIGN—COLLIERY SWITCHGEAR—TRACTION SCHEMES—CENTRAL STATION—SUPPLY SCHEMES—METHOD OF CONTROL.

THE divergence of opinions in matters relative to switchgear design is so great owing to its varied classification and nature, that it is exceedingly difficult to place at the disposal of engineers principles upon which designs should be based.

It is not the intention of the author to deal exhaustively with the subject, but to place on record diagrams and results obtained within the scope of his experience in design.

It can safely be stated that in no other branch of the electrical industry are there so many problems commanding the imaginative genius of designers as in that of switchgear control.

The subject is so expansive that even manufacturers have limited their scope of designs in order to effectively treat or specialize on a particular section of equipment. Thus we find firms specializing on D.C. control, while others specialize on A.C. gear, and even these sections are subdivided in that some companies manufacture, say, D.C. motor panels; others, starters; and so on.

Apart from standardization and economic considerations the ability of skilled artificers in producing varieties of gear is limited. For instance, a mechanic trained to produce heavy low tension switches would not produce switchgear for high potentials equally as efficient, and the difficulties of labour in this connexion are more pronounced, as the development of designs proceeds.

In factories where all varieties of design are produced, the establishment charges for such productions are out of all proportion to the results obtained and the standard of efficiency is impaired.

As far as possible, therefore, manufacturers specialize and produce a definite series of designs for a market to which they are particularly suited.

The same conditions apply to designers and technical experts, and those who have only studied the conditions of high pressure service are not warranted in attacking problems outside its scope. To mention some of the various specialities of switchgear makers I would refer as below:—

(1) Production of switchgear for Government and Admiralty service.
(2) Production of switchgear for low tension supply undertakings.
(3) Production of switchgear for high tension control.
(4) ,, ,, for colliery service.
(5) ,, ,, for industrial conditions.
(6) ,, ,, for E.H.T. currents.
(7) ,, automatic control devices.
(8) ,, current and potential transformers.
(9) ,, indicating instruments.
(10) ,, static relief dischargers.

The above are primarily divided into two classes, namely, for high and low tension service, the application of such gear being limited to its proposed sphere, and governed by the requirements of the service on which it is installed. The distinction between Admiralty and industrial

service is a very wide one, although primarily they serve the same purpose. The action of sea water on corrodible metals and the ability of the gear to withstand shocks, in the one case,—while in the other the provision of industrial control is the only limiting feature,—widens the sphere of design so much that the designs for either application are as distinct as, hypothetically, switch and circuit breaker.

Again, switchgear for the control of electric supply to an ironworks contains different features to such apparatus as is used in a cotton mill, where the conditions of service are altogether different and demand the skill of a designer who is acquainted with the circumstances under which it is employed. Thus it is found that repetitional designs of switchboards vary so much that standardization is practically impossible, and such boards are only capable of production in the form of links that perform separate functions.

Each firm manufacturing switchgear, if intent on supplying proper designs and satisfying clients, should employ those whose ability is identified with this branch of industry and not rely upon the ability and technique of, say, a motor designer, as such a course will lead to disaster. Even admitting the necessity of special ability in a switchgear designer, it by no means ensures ability in dealing with all the departures switchgear covers, and no conscientious man would be prepared to undertake such work, knowing that the subject is too wide for his individual scope.

Switchgear for High Pressure A.C. Service.—The introduction of high speed turbo generating sets and the development of large power supply undertakings has naturally affected the design of switchgear and introduced new features in lay-outs that hitherto were outside the ordinary industry of this country.

The common use of extra high pressures, such as 6,000 to 10,000 volts, or even 60,000 volts, which a few years ago

would be looked upon as preposterous, has also assisted in the production of designs and their application. The means provided, to not only protect such schemes from failures and breakdown, but to maintain continuity of supply, are very ingenious, and it must be remembered that the success of a supply undertaking depends almost entirely upon the successful operation of its control. Any new introduction that will add to its safety, therefore, should be welcomed, and initial cost considered a secondary feature when such a large amount of money invested in machinery is at stake. Many of the new designs, however, are not beyond criticism, there being a general tendency to perfect their electrical efficiency at the expense of mechanical strength, robust construction and simplicity being of paramount importance. Again, the anxiety of engineers to purchase or provide protective systems on their transmissions has been carried to such an extent that their object has been defeated by the introduction of additional links, which increases the liability of failure. The most effective protection on any system is usually the simplest.

The trend of modern design in high tension gear has lately been subjected to a great amount of criticism, due to the large number of fires that have occurred in the last twelve months. Out of seventy fires or breakdowns due to generated arcs, forty were principally caused by lack of provision for confining the generated arc to its own immediate neighbourhood. In some cases no means were provided for sectionalizing the power units, which resulted in a complete shutdown of supply. Competition, especially where the supply is greater than the demand, has been largely responsible for the absence of necessary gear, and the inadequate provision of space for its reception. Apart from the chief functions of switchgear control, it is necessary that the gear provided should be so arranged as to prevent accidental contact and so interlocked that cleaning and inspection can only be done when the appara-

tus is "dead." Even if interlocking is provided, suitable indicators should show whether the gear is alive and show also its potential. Accidents are continually being reported of severe shocks and deaths caused by designs not permitting adequate inspection and maintenance. It must not be inferred that the designer is at fault in this respect, rather the purchasing engineer or his agent, as in most cases specifications are issued which insist on the nature of design, and any attempt in a great many cases to point out faults would be objected to, incurring the displeasure of the client, and placing the designer in a position where he would be likely to lose business. Part of the training of a designer who interviews customers is in the ability to use tact, so that he can bring home his points without subjecting his client to annoyance, a by no means small proportion of his duties. If clients would only realize the experience of the manufacturer and listen to his suggestions, a great many designs could be produced that would be proof against the accidents and failures experienced now, and it is noticeable that engineers are realizing this and co-operating towards this end. Out of sixteen specifications received by one company for H.T. switchboards in one week, only two were practicable, and even these were admitted to be incorrect. To illustrate the above remarks an extract is given below from the report of H.M. Inspector of Factories dealing with fatalities that have occurred in connexion with bad switchboard design.

Extract of Report of Fatalities.—"Referring to examples of dangerous conditions of electrical plant which I have come across during the year, it is instructive to note the carelessness, and in some cases the indifference, shown to the dangers which are in evidence, even in recent work, and in quarters where one would expect to find the exercise of due care quite irrespective of any regulations. Thus I found in 'central stations' of authorized electric supply undertakings a number of dangerous passage-ways, some

where there was no protection whatever, at the high or extra high pressure conductors or apparatus, not even cellular divisions between the different panels or conductors. In some cases the blades of isolating switches were in the 'live' position, and projected into the fairway of the passage in two cases, just at the entrance, where a person would most likely inadvertently come into contact with them. The complete absence of any protection in the case of substations of one local authority was admittedly due to the 'desire to keep down capital expenditure,' yet in the generating station there were 'Art tiles,' 'oak panelling,' 'Mosaic floor.' In the high pressure generating station of a local authority the switchboard, although not new, had been recently remodelled, and had dangerous passage-ways, one having exposed live conductors at high pressure on each side, the width of the passage-way between the live conductors being only 2 ft. 6 in. In the generating station of an electrical supply company the main high pressure switchboard, not more than two years old, had a narrow passage-way at the back containing the switches and other apparatus along the side. There were bare conductors from these to the busbars, placed immediately above the passage-way, only 6 ft. 6 in. from the floor, no partition whatever being provided; the passage-way was, however, closed by a locked gate. There is, of course, no objection whatever to such an arrangement, providing no one is allowed in the passage-way while the conductors are alive. In this case the whole plant would have to be shut down if cleaning or other work had to be done, there being no means of dividing the board into sections. This arrangement, however, shows an extraordinary want of forethought in the case of a company giving a statutory supply which must necessarily be maintained continuously. The switchboard, therefore, requires remodelling, otherwise at such times work having to be done, some unfortunate attendant would but for the regulations have to risk his life. In a transforming sub-station

belonging to the same undertaking the medium pressure distribution board consisted of switch fuses fixed on the wall behind the transformers. The extra high pressure lead to the transformers were brought up in front of them, and from the top, 12 in. or so, the insulating material had been removed from the cables and a layer or two of ordinary wireman's tape had been substituted. These tail-ends of the cables were quite unsafe to touch, and yet any one having to use the switch fuses would perforce have to lean against them, the arrangement being a death-trap. In the same sub-station oil-immersed fuses were provided. No oil was in use or provided; whether this was due to motives of economy, did not appear. Not only safety but ordinary convenience has often been sacrificed by unnecessarily cramping up the plant and apparatus.

"In the main sub-station of a public supply undertaking, having a bulk supply from a power company, cramping was totally unnecessary, as ample space existed in the building; but it was decided to try to augment the income by letting off a portion as a shop. In some underground sub-stations the floors were covered with water, due to leakage through the structure. This fault, which is often a difficult one to deal with, adds considerably to, and is often a permanent danger.

"Regarding a fatal electrical shock in a coal mine which occurred on a concentric system, with bare outer conductors earthed at the generating station, the branch circuit where the accident occurred had fuses in both conductors, the outers had become charged up owing to the earth connexion having been broken by reason of the fuse having been blown, while those of the inner continued to hold. There should, of course, have been no fuse or break of continuity of any kind in the outer conductors. There was a local earth connexion beyond the fuses, but it did not prevent the outer conductor from becoming charged, so that the man who grasped it was killed. This local connexion was made to

the water-pipe nearly 200 yards in length and partly lying in water. The connexion, however, was loose both on the outer conductor and water-pipe and therefore did not make good contact. Hence the necessity of having sound earth connexions."

From these and other reports it is obvious that too much thought cannot be applied when considering designs for the control of electrical machinery.

Adverting to a further few illustrations of bad design of boards it is also noticed that considerable loss has been caused by very small departures from the orthodox method. In one case, on a high tension board, the main field and exciter resistances were fitted below the oil switches, oil trays not being provided; the oil leaked from the tank of the switch and saturated the resistances, so that when these reached a high temperature the oil caught fire, and not only burnt the whole of the board but the fire travelled along the rubber-covered cables, laid in ducts, to a colliery about 700 yards away, involving the loss of some thousands of pounds. In another case the arc flashed over the leading-in insulator to the frame and caused a short across the bars. This short was a very severe one, as the whole of the station, 18,000 K.W., was on load, and resulted in a complete shutdown of supply. It is quite an easy matter to describe these shorts, but it is not so easy to illustrate their effects, and unless these have been experienced the serious nature of such accidents is never realized. These will become more severe as time goes on, due to the greater ability of prime movers in standing up to such stresses. In one station in the south of England the author was present when such a short occurred, which practically demolished the building and in such manner that the station had to be rebuilt. If this could be realized, very few limitations would be forced on to the designer.

General Principles of Design.

(1) Gear to respond with precision when called upon to operate, and to maintain continuity of supply.

(2) Simplicity of design, as the introduction of additional links increases liability of failure.

(3) Robust construction and liberality of design.

(4) Inflammable material to be avoided as far as possible and due provision made for localizing fires.

(5) Gear at high potentials to be protected from accidental contact.

(6) Provision for access and inspection and for making such gear "dead" without disturbing continuity of supply.

(7) Protection in the shape of relief for abnormal conditions.

The constructional portion of the switchboard is determined, chiefly, by the space available and the plant to be controlled, space being of importance and limited for sub-station work.

Sub-Station Ironclad Board.—Figs. 1 and 2 illustrate such a board, which controls three transformers and

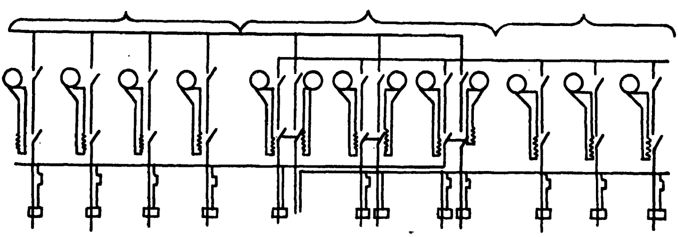


FIG. 1.—Ironclad Sub-Station Board.

feeders on a two-phase 3,000 volt distribution, the outer of which is earthed. This design will commend itself chiefly on the ground that such a board occupies a minimum amount of space without unduly cramping the internal gear.

Fig. 3 represents a similar sub-station board controlling

feeders and various circuits on a 10,000 volt fifty period distribution, neutral insulated.

As iron enters largely into the construction of the board, there is less attendant danger due to same being at "earth

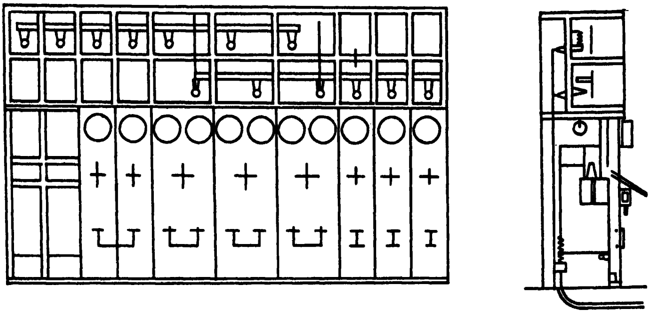


FIG. 2.—Diagram of Connexions.

potential" than with a board which consists of moulded or other insulating materials which are never free from conducting mediums, *e.g.*, slate with metallic veins, and stone with porosities which render it hygroscopic. For this

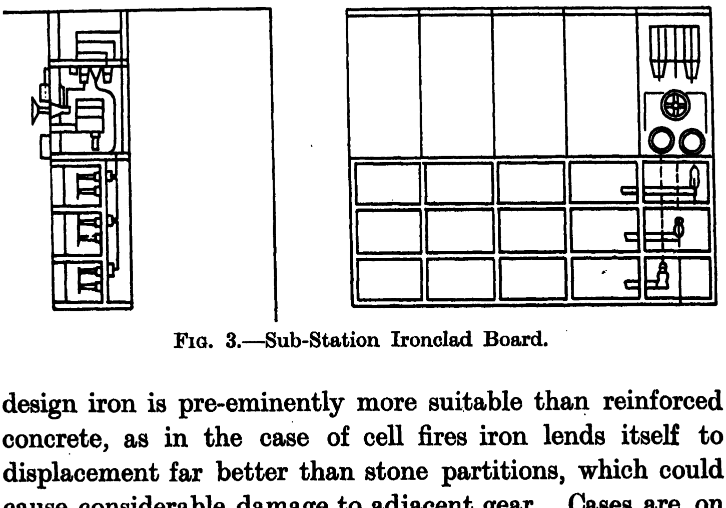


FIG. 3.—Sub-Station Ironclad Board.

design iron is pre-eminently more suitable than reinforced concrete, as in the case of cell fires iron lends itself to displacement far better than stone partitions, which could cause considerable damage to adjacent gear. Cases are on

record on the Continent, where several severe explosions occurred, and photos can be produced showing the results of the disasters for comparison. Iron under explosion has a tendency to fuse or bend, whereas stone under the same conditions tends to wreck all the adjacent cells in its immediate neighbourhood. On a hydro-electric scheme in Canada this year an explosion in one stone cell destroyed all the adjacent cells, eighteen in number. It must not be inferred from the foregoing that stone cell work should be discontinued; as a matter of fact, iron, under other conditions than represented above, would be equally dangerous in use. It is practically impossible when designing switchboards of large killowatt capacity to use material other than stone, especially where the switches are remote controlled either mechanically or electrically. The isolating switches in the previous illustrations are shown to be operated by an insulated hook, this method being quite common on all modern designs. Where extra precautions are necessary for safety, isolating gear which is operated externally is to be preferred, as in the former case the attendant must necessarily enter the danger zone before the board can be rendered "dead." In the latter case the isolating switches are off before the cell door can be opened and access gained to its interior.

First Form of High Tension Board.—It is interesting to review the various stages between the first design for the control of H.T. currents and the designs that are now used, all of which were produced to suit the requirements of the period and to satisfy the ideas of the parties responsible for their introduction at a time when experiment and research work were unknown. Even now research and the obtaining of accurate data is left to a limited few, and obsolete ideas still permeate the industry. Objections and difficulties are placed in the way of any engineer thirsting for knowledge, and even if such is acquired it is received with disfavour and discounted in the fear that such

knowledge will supersede principles founded on surmise. The first experiments conducted by the author with the aid of the oscillograph were met with every possible objection, and it was only after twelve months' agitation that such experiments were permitted. These tests proved theories quite opposite to those held at the time, and which were absolute, as the record of an oscillograph cannot be disputed. The tendency of design is to copy one or another's manufacture, incorporating their particular ideas, whereas design should be primarily based on principles derived from accurate data. Insensate competition and the controlling interest of those who rule the industry and have no intimate knowledge of technique are responsible for the failures.

Fig. 4 illustrates one of the earliest designs for H.T. control. The switches were of the air break pattern, operated by long handles and levers. The controlling principle of design was the limitation of space, whereas to-day such limitation is most undesirable. This type of design is still in use and has performed its duties well, and may even now be used for low currents at medium pressures. With the introduction of large power units this was discontinued, and was followed by the water and oil switch design. It will be seen that extensions were a very difficult problem and that no provision was made for inspection or rendering such a board "dead" for cleaning purposes. As a matter of fact hardly any of the conveniences now necessary are incorporated in this design. The protection consisted of "oil immersed fuses." These are still manufactured for small currents and in some cases may suit the conditions better than the orthodox automatic oil switch.

Switchboard Structures.—Apart from continental practice there are now four general forms of structural cell work: (1) Moulded stone; (2) Reinforced concrete; (3) Brickwork; (4) Iron panel work.

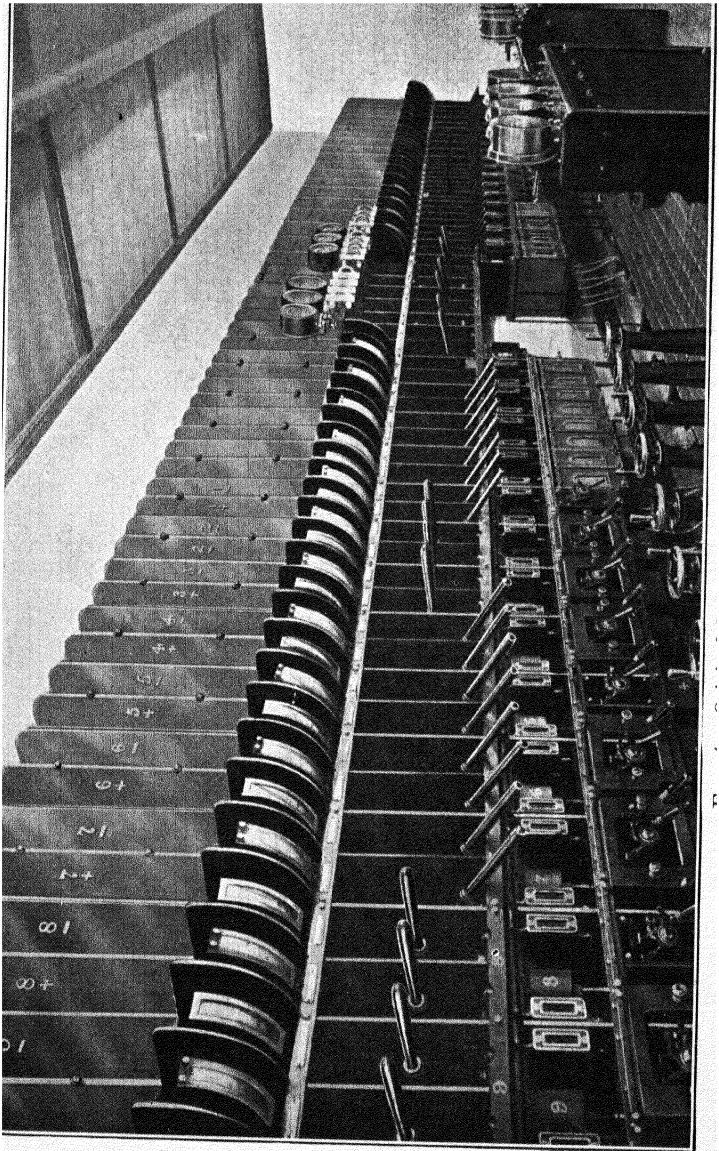


FIG. 4.—Original H.T. Single Pole Cellular Board.

1. Moulded Stone.—This consists of many mixtures, the two principal ones being "sand" and "cinder," general experience proving that the latter is most satisfactory. The proportion used is one part cement, two of sand and four of clinker. There is less danger of fracture and drilling is easier than with stones of the sand type, and, while much lighter, it is more substantial and elastic. The sand mixture is composed of one part cement, two and a half of sand and half gravel or granolithic stone. The surface of this mixture is smooth, but it is exceptionally brittle. In both cases the mixture must be wet, well puddled, and allowed to dry for at least eighteen hours, without artificial heat. If artificial heat is employed the mixture becomes unnatural and lacks homogeneity. To obtain a first-class appearance the stone surfaces, after being cleaned, are faced with a thin mortar cement, which is applied after the slabs are dried by means of a wooden trowel. The presence of air holes and clinkers affords a good binding for the mortar covering. This method is very convenient for making slabs of any size, and such holes as are necessary for the fixing of the gear should be bored during process of drying. Busbar cells can be constructed in one pouring and porcelain insulators moulded in the slabs.

2. Reinforced Concrete is constructed similarly to moulded stone, but in order to obtain mechanical strength expanded metal sheets are embedded in the centre of the slab; in some cases iron rods or bars are used. The objection to the expanded metal sheets is the difficulty of keeping same in the middle of the slab, and its effectiveness against side strains is somewhat doubtful. Also the act of drilling holes for fixing the gear may lead to inconveniences and cause piercing of the sheet, which must necessarily weaken the insulating properties. Several experiments have been made to ascertain the most durable of these two forms of structure, and it has been found after a certain period

that electrical corrosion of the iron reinforcement has taken place. This, of course, is very dangerous, and where extra high potentials are present, reinforcement is not permitted on any account.

The first factor to determine stray current and voltage is at what voltage corrosion of ordinary unstressed steel will occur. The usual limit is defined in the neighbourhood of 15 volts, and any voltage above this is a decided "leak." Therefore any test above this limit is forcing conditions on the concrete which are not likely to remain undiscovered in any electrical circuit. It is such currents and voltages as are likely to remain undiscovered that need study. Tests are produced showing the result of corrosion at 1·1 volts, and it appears generally to be in the neighbourhood of 3 to 5 volts that ill-effects show themselves in course of time.

The specific resistance of concrete and cement is of the order of 1,000 megohms per cubic centimetre.

The conductivity of concrete depends upon its porosity and the amount of moisture absorbed. When the pores are full of aqueous sodium chloride this condition makes for fairly good conductivity and it is easier to extract moisture from the concrete than to render it impervious with resisting compound. Low density currents do not affect the compressive or tensile strength of concrete unless reinforced.

When the current leaves the iron through an aqueous solution, oxygen, and possibly chlorine, would be liberated on the surface of the iron. If so an iron oxide is formed, accompanied by chemical changes which increase the volume. When iron is changed to ferrous oxide (Fe_2O_3) the volume is increased in the ratio of 1 to 2·2.

No scientific data is available bearing on the resistance offered by mechanical pressure to chemical action, but it is known that enormous forces are at work and such forces break the concrete. Of course it may be said that alternating currents do not set up electrolytic action. This is so theoretically, if the currents in both directions are

exactly equal, but as stated before, when currents assume such dimensions as to cause heating, or if the positive and negative waves are unequal, the same ill-effects are observed in due course.

Stray currents depend upon :—

(1) The thickness of concrete.

(2) The proportion of salt solution in the surrounding electrolyte.

(3) The density of the mass and proportion of its ingredients.

In many instances the embedded iron is coated with a preservative paint, or has an aluminium surface. This, however, is not good practice, as economic considerations enter the problem.

In all forms of concrete work there is a lack of standardization. This should not be so, as one set of moulds can easily be made to meet the general requirements of the trade. Thus one set of moulds can be made for busbar cubicles, another for isolating cubicle, one for oil switch cubicle, and again for transformer cubicle, each set being duplicated or triplicated as required for either single, two or three phase design. The shipment of such material is then only a matter of routine. The fixing of the internal gear to the structure should not be by iron channel or framework bolted to it, as the above arguments will show, but if possible the iron framework should be separate and unaffected by the varying conditions found in stonework.

To all forms of concrete cell a copper earthing strip should be fitted. The usual thickness of slabs is between 2 in. and 3 in., but when dealing with potentials of 30,000 volts upwards the thickness should be increased and the design of such cells enters a totally different sphere.

3. Brickwork.—This forms an excellent structure and embodies most of the points raised under moulded stone, with the advantage that it presents an excellent appearance, and, if glazed, is much more cleanly. Its popularity is de-

pendent upon the labour market, as trade unionism has forced contractors to use materials that are not governed by laws and restrictions. Enforced privileges and so-called "rights" are more pronounced in the building trade than in any other industry, and the losses incurred have caused contractors to particularly avoid this form of construction. On the other hand the plugging and fixing of the internal gear is much more difficult than when applied to moulded stone.

4. Iron Panel Construction.—If the board is built on similar lines to those shown under Figs. 2 and 3, an iron structure is most efficient. In order to present a first-class appearance planished steel with nickel facings may be used for the compartment doors, and the earthing of such renders it absolutely immune against contact and other dangers associated with the concrete form of construction. Shocks are eliminated, and in places subject to rapid condensation it is essentially the best practice. It is, however, not feasible to construct a board of iron when dealing with heavy power units, or where the gear is either electrically or mechanically remote controlled. Manufacturers are identified with their designs, and in many cases industries have been built up by the introduction of notable improvements. Anxiety to create this impression has, however, in some cases had a negative effect; for instance, there is the carrier form of switchboard, the chief feature of which is ability to withdraw the interior for inspection without disturbing the structure. The demand for a form of panel to enclose entirely all the internal apparatus has also caused certain set-backs in design. Cast-iron panel or pillar construction is by no means as flexible as the sheet panel referred to above, and modifications are rendered more difficult. Dealing with some of the points observed in one of these designs, the current transformers were embedded and fitted in solid compound; imagine the difficulty of making any minor alteration, having first to chip or melt the compound,

and the conservation of heat generated by the passage of the current. The potential transformers were fitted in the switch tank. Such transformer must necessarily give off heat, raising the temperature of the oil, and, under certain circumstances, causing inflammable vapours. The switch on opening must clear the oil to a certain extent, thus a considerable amount of semi-conducting carbon is present in the insulating fluid round the transformer. Again, the design is used for colliery work under gassy conditions, yet the switch cannot be withdrawn without a spark occurring at the contacts due to the capacity between it and earth, even if the oil switch contacts are in the off position before removal; since the compartments are filled with compound, this again may form an explosive gas which may collect in the pockets of the switch terminal.

As the interior mechanism has to be withdrawn this must necessarily mean male and female contacts. These are not good practice and it is impossible to see if they are lining up properly. Heating may occur and cause cracking of insulators, etc., no one being the wiser. Male and female contacts were used in prehistoric days for direct currents, but are now practically discarded owing to difficulty of guaranteeing good conductivity, it being a practical impossibility to construct them without large watt losses, especially when used for heavy currents. The most important criticism, however, centres in the position of the oil switch, which is unprotected, and in front of the operator. Should this switch burst or force oil out, the danger can well be imagined. This criticism is not directed against any particular manufacturer, but is commended to the attention of switchgear designers generally.

Double Feeder Panel.—Figs. 5 and 6 illustrate a double feeder and generator equipment. This illustration is only intended to show their constructional arrangement, the material being moulded stone. Double feeder and generator panels are very convenient for the formation

of a ring busbar equipment and occupy a minimum of space. This design was installed on a 6,000 volt, fifty period distribution. The capacity of the station was 26,000

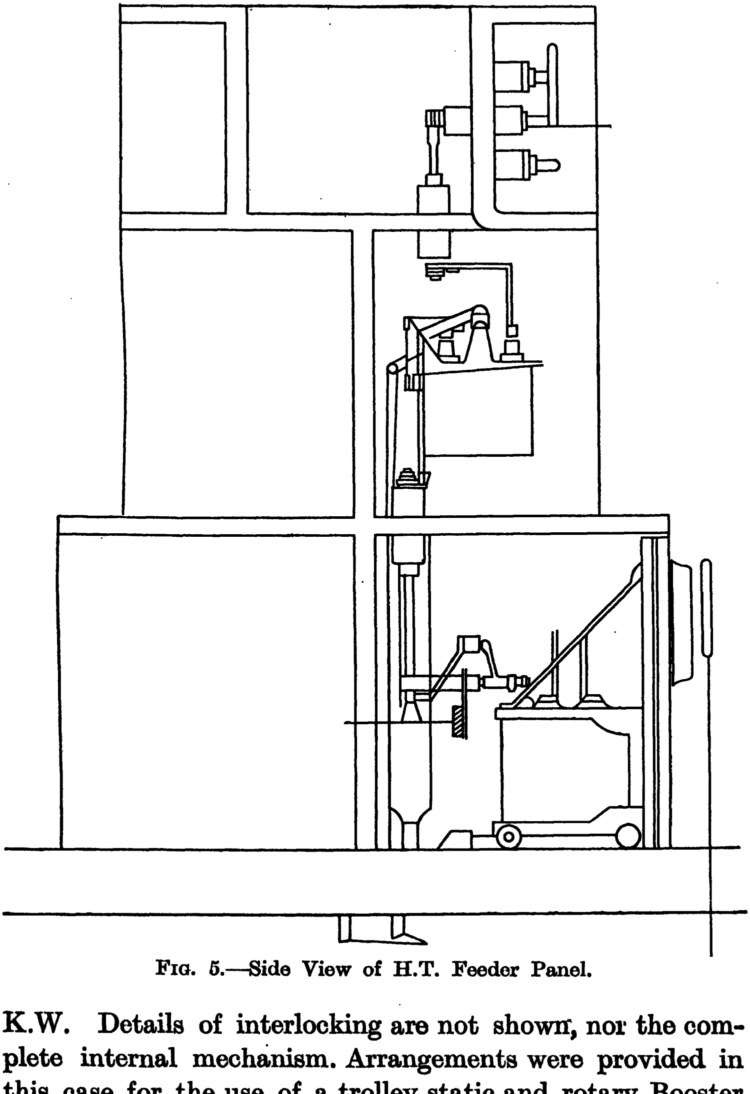


FIG. 5.—Side View of H.T. Feeder Panel.

K.W. Details of interlocking are not shown, nor the complete internal mechanism. Arrangements were provided in this case for the use of a trolley static and rotary Booster

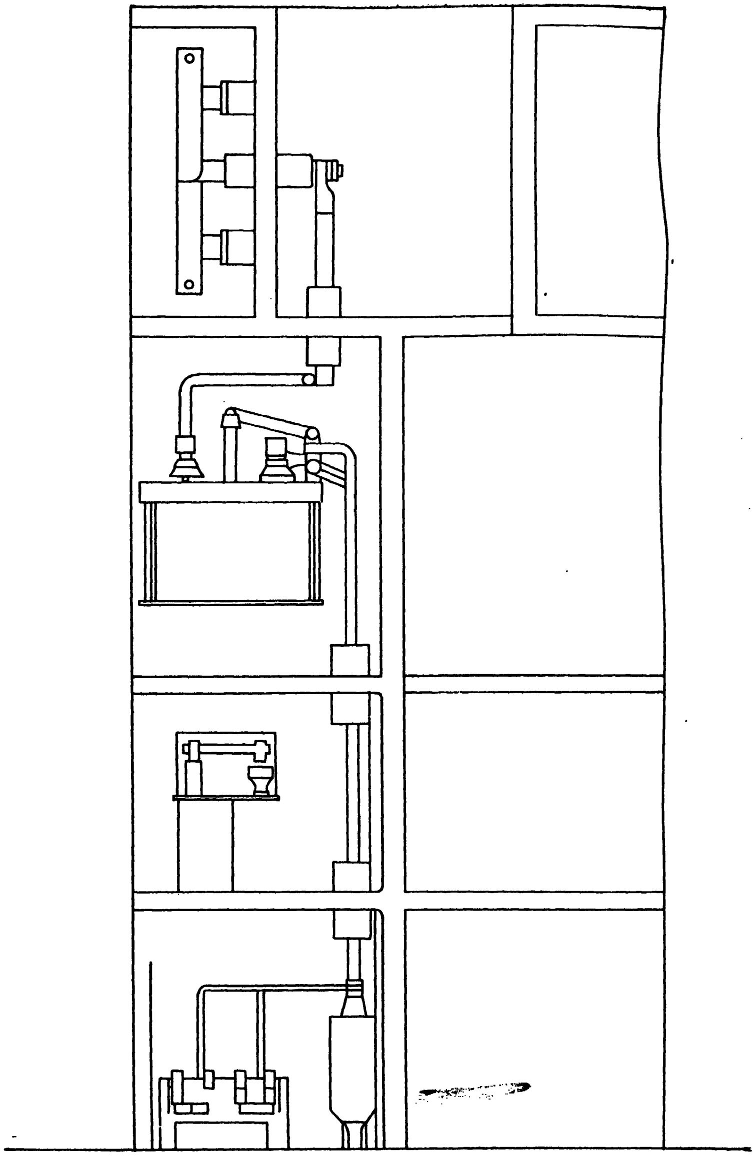


Fig. 6.—Side View of H.T. Generator Panel.

and permitted its insertion on any particular feeder. A remark might be made here on the introduction of asbestos panel doors. Iron panel doors are heavy and in some cases unwieldy in size, hence in this case asbestos doors were introduced, strengthened by lignum strips to prevent warping, which up to the present are very satisfactory. Thus a slight addition is made in order to obtain fireproof cell work.

Interlocking Gear.—Interlocking the internal apparatus has of late years been very prominent in the construction of switchboards, chiefly for two reasons: first, safety, and second, the requirements of Home Office Regulations. It obviously serves no useful purpose if the isolating switch is so interlocked with the door that when the former is in the "off" position, adjacent gear in the same cell is alive. This is mentioned because it is common practice to fix the busbars in the same cell as the isolating switch, hence although one end of the isolating switch is dead, the other is alive if the plant is on load. Again, even supposing that the busbars are in a separate cubicle and the incoming connexions are isolated or made "dead," there still remains the high tension terminal connected to the busbars, which is alive in the cell, and, as in the former case, is even more likely to cause an accident, since an attendant might be under the impression that the whole gear is "dead," seeing that the isolating switch is in the off position. Another fault often occurs on a generator equipment, e.g., in the case of an incoming feeder to a sub-station the isolation switch is on the busbar side, no provision being made for isolation on the incoming side. Thus one side of the equipment is alive, and an attendant might naturally suppose the gear dead with the oil switch and isolating switch in the off position. It will be obvious to any one that the danger of fatal contact is increased rather than diminished, unless the switch renders the compartments absolutely dead. All terminals should be shrouded and made "dead" when the compartment is opened; the mode of isolation must be such

that it is possible to inspect the gear under normal conditions; if this were not so, there would be no knowledge of the behaviour of the switch contacts, etc., and considerable trouble may be developing, which might not be discovered until too late. Isolating switches operated by hooks are not such good practice as when isolation can be effected from the exterior of the panels, as in the former case the operator to render the compartment " dead " must first open the door, thus entering or exposing the danger zone, and cases are on record of fatalities caused by so doing. In the last case reported, an attendant stood on some steps with the hook to open the switch, when the steps gave way; he grasped the live portion of the cell in falling, and was killed instantly. The ideal interlocking, from a safety point of view, is such that the internal gear about to be inspected is made dead before the compartment door can be opened; that is, the isolating switches must be operated externally to the gear. Isolating switches should be interlocked with the oil switch so that the latter must be in the " off " position before the isolating switches can be removed; the door of the compartment should also be interlocked with either one or the other, so that both must be opened before the cell door can be removed. In this connexion manufacturers determine their own scheme, some by fixing the blades of the isolating switch on the cell doors,and others by internal mechanism; so long as the safety precautions are observed in workmanlike style, no laws are necessary to govern designs in this respect. It is often the practice to fix isolating switches at the back of an open type panel; their use as regards safety is negative, but they may be found convenient for opening up a panel equipment for inspection purposes; apart from this there is no utility in the design. Earth contacts are advocated on isolating switches, so that when the switch is in the off position the leads to same are " earthed." This is of great value in some cases, e.g. in the case of a sub-station

where the supply cannot be continued during repairs until the earth is removed. The author had an experience of this nature. While adjusting contacts on the isolating cubicle, for some reason or other the circuit was made alive at the power station, 5,000 volts. The shock threw him off the ladder over a 250 K.W. power transformer. That it did not prove fatal is the more remarkable. If the circuit is earthed it cannot become charged during repairs.

Magnetic Strains of Isolating Switches.—An important point in the layout of a switchboard is the position of its parts in relation to the flow of current. It has been found that isolating switches and disconnecting fuses have opened under magnetic strain at full load, and such a catastrophe may be attended with serious results. Instances are as follows : In one case, owing to the isolating switches opening under load, severe arcs were set up, which melted the contacts,. placing a short upon the entire station ; needless to state, the whole equipment was burnt out. In another the disconnecting fuses were blown across the power station, injuring the attendant. There are many theories advanced for this magnetic phenomenon, and experiments have been conducted to account for it. The results point to the fact that in passing a current through a conductor the magnetic forces distort the latter in such wise as to increase its length. Thus the switchboard internal connexions are subject to magnetic distortion and mechanical strains which evidence themselves at the instant of parting contacts as a species of mechanical expulsion. Such phenomena only present themselves in stations of large kilowatt capacity.

The internal connexions of switchboards should be only of bare copper rod or strip. Any form of insulation that is not fireproof should be excluded. The connexions should be as straight as possible and bends avoided, as such introduce inductance of a greater or less degree. All small wiring should have fireproof insulation and be neatly arranged so that each separate connexion can be easily

traced out without coming into contact with main connexions and can be removed without disturbing other current-carrying parts. All contact studs should be provided with spring or Thackeray washers, to withstand the vibration caused by alternating currents. Soldered connexions are not advised. Cone connexions are excellent practice and are ideal for main connexions; the utmost importance attaches to good mechanical and electrical contacts, particularly in the case of heavy duty switchgear. It must be stated that the value of any form of high or low tension switchboard is judged from the back and not from the front appearance. A switchboard may present an excellent appearance in front, and be totally incapable of performing its functions owing to the bad design of gear situated at the back. The secret is to design the back efficiently so that the apparatus exposed on the front presents a good appearance and is proportionately arranged.

Ring Form of Busbars.—While the position relative to isolation and interlocking has been discussed, there remains the question of isolation of such sections of busbars as require attention. The most convenient form of sectionalizing appears to be that conducted on the ring principle. The difficulties are apparent, seeing that this vital portion of the gear requires making dead without discontinuing the supply. Often a busbar insulation breaks down, or the collection of dirt and dust requires attention, and in such cases the bars must be rendered "dead" before repairs or cleaning proceed. Most supply authorities are unable to entirely cut off supply at any period, thus the latter has to be diverted into a separate channel to that needing inspection. The ring form of busbar meets this condition admirably, inasmuch as current can be supplied in either direction and a section isolated without interrupting the supply. Such sectionalizing switches, however, must be of the oil type, as they have to break current, and paralleling gear should be provided in case the ring form of bar is

converted into a duplicate system. It might be considered policy to use duplicate bars for this purpose, but such an installation is more costly than the ring form equipment. Apart from the liability of errors in operation the gear so arranged is not so simple and errors not only in management but in readings are more likely than on a board of the ring form of design.

Nearly all modern designs where this contingency is to be met are constructed on the ring form principle, except in stations where ample capacity is reserved and a change over principle of distribution is involved. Fig. 7 illustrates the method adopted in so-called ring distribution. The feeders can be changed over to either set of bars and current supplied in either direction. Any portion of the gear can be rendered "dead" without interrupting the supply; means for paralleling are also provided. In some cases sectionalizing is adopted for the purpose of sub-dividing plant, so that, if run in sections, a short on one will not interfere with other normal working sections. This is very desirable where the supply must be maintained at all costs, as for a railway, since the dislocation of traffic is more serious in crowded cities than failure of electric light. Although such section switches are provided they may not always be used in emergency, and a failure of one of our largest stations was brought about in this manner, all the sets being in parallel across the bars at the time of disaster. In this case the transformer flashed over, which resulted in the oil switch being shorted, thus shorting the whole supply, and causing a complete shutdown.

Busbars should be divided up between phases, so that the latter cannot be shorted by accidental contact or by conducting material, such as a spanner, crossing the phases. These precautions are of course necessary in respect to stations of a public supply undertaking. The design of a switchboard for collieries is governed by its environment.

Colliery Switchboards.—Fig. 8 is a diagram of con-

nexions used in one of the collieries in South Wales. This design was introduced before leakage protection became of great moment, although leakage indicators are shown. Due to the class of labour employed in collieries the gear must be more fireproof than in stations where highly-trained men are in charge. It is not intended to convey that engineers in collieries are of a lower order; this is not so, but the gear is subject to the control of minor officials, whose duties are not identified with switchgear matters, whereas in the other case the switchboard is under the care of an operator who has specialized in the subject. Again, the regulations are different to those adopted by supply authorities. If a leak occurs the circuit must be relieved before the arc comes in contact with the external atmosphere. Automatic action can be secured in a variety of ways. A very convenient form of protection if armoured cables are used is by the insertion of a coil; thus, before the leak current enters the outer field, it must necessarily pass through the coil, thus operating the switch before the arc appears. One objection to this form of protection is the case when the cable is entirely severed by falling masses or props. At such times the armouring is severed before the copper cable, and no current passes through the trip coil circuit. One of the greatest difficulties met with in arranging for efficient protection is the use of trailing cables for coal cutting machines. These conditions have, however, been met, and will be discussed later on. Concrete cubicle construction should be avoided for switchboards controlling energy on colliery distribution, and such boards should control only those cables that go to the pit bank, where a separate board should be provided to control the underground circuits. There are many cases where the cables from the main switchboard pass down the shaft and the bank to the "header," but this practice is recognized to be wrong, as such a feeder cannot be adequately protected, apart from the other inconveniences incidental to such an arrangement.

Primarily, however, the design should incorporate safety for inspection, simplicity and robustness. Earth detectors are insisted upon, and protection must be of a simple nature. Balance protection, the introduction of pilot cables, or any delicate mechanism should never be incorporated in such a design. It must be understood that at the present time electrical power is strongly opposed by compressed air, whilst the miners are very suspicious and oppose everything electrical, and any innovation that does not contribute to the safety and interests of those who work below should be immediately condemned. This is not the field for experimental research, seeing that many lives depend upon the success or failure of any such innovation, and examples are given later in this book where life has been sacrificed by lack of efficient protection. The question of switchboard design for collieries is more serious than in any other branch of industry.

Traction Equipments.—Fig. 9 is a diagrammatic arrangement of a traction equipment, and is supposed to represent the latest practice. The questions concerning its design are referred to in the direct current section. This board also controlled lighting feeders and possesses some very novel features. The operating board was of bench form situated in front of the gallery, and the protection was such that in the event of abnormal conditions arising the section affected was relieved without disturbing adjacent sections normally on load. While a lengthy discussion could be continued on this design, it is not the intention of the author to point out the good or bad points, but to continue further on other matters which incorporate identical features, the diagram being sufficient for illustrative purposes. Fig. 10 illustrates in diagram a 6,000 volt scheme with duplicate busbars referred to previously, and Fig. 11 illustrates an A.C. and D.C. combined scheme for lighting and traction. Either of these diagrams represents modern practice with details involved by the special requirements

of each individual control. It is intended that such diagrams may be useful in any suggested layouts and may be taken as a basis.

Control Board Design.—Only low tension currents are dealt with by the control board and it should be used primarily for the indicating instruments and such gear as is necessary for the actual operating of the equipment. The type of board is decided by the amount of space available, and in many instances where space is limited or the width of the gallery is a minimum, a bench construction is adpoted. There is a distinct preference for this design, as the operator while at work can keep the station and plant under observation. This is impracticable with a flat back board, as the latter is too high for fixing at the front of the gallery, and, while observing the instruments, the operator has his back towards the station. This is not an important point, but convenience can be considered when deciding. On the other hand, the gallery need only be 3 ft. 6 in. wide, plus the width of the board, say 2 ft. when using the bench form, whereas with the flat type of board the gallery must be 7 ft. wide to conform to regulations. Rheostats should be pillar controlled and operated independent of any other gear, the resistances mounted in a position apart, constituting the equipment. As insulation is not entirely an important factor with such low tension currents, appearance and durability rule the decision as to whether slate or marble shall enter into the construction. Marble is subject to discoloration and appears in time full of stains; enamelled slate on the other hand does not suffer from this drawback, but scratches are very difficult to remove.

CHAPTER II

Oil Switches—Kilowatt Capacity—Current Increment—Potential Rises—Power Factor—Internal and External Reactances—Inductive Capacity Effects—Time Delayed Switches—Conservation of Energy—Dissipation of Heat—Short Circuited Currents—Interchangeability—Method of Calculation—Oscillograph Effects—Pressure in Oil Tanks—Design of Tanks—Insulators—Action of Switch Mechanism—Contacts—Character of Di-Electrics — Condenser Terminals — Corona Phenomenon—Surges — Oscillation s— Calculations — Earthed and Unearthed Systems—Oil Switches for D.C. Currents—Gastight Provisions—Colliery Conditions—Inductive Rises—Dissipation—Carbonization—Oil Switch Tests—Water Switch—Oil Switch for Heavy Duties—Remote Control Gear—Interlocking.

Oil Switches for A.C. Circuits.—The quality possessed by turbo generators of standing up to their work, greatly increases the destructive effect of a short circuit. In some cases inductance has been deliberately introduced into the generator leads in order to check the sudden transmission to a circuit of the accumulated energy of the generator; and it is generally recognized that prompt opening of the circuit is essential, or the task of disrupting the rapidly rising current may prove very difficult. It is realized that under certain conditions destructive energy is generated and liberated in the relief of an external electrical disturbance, and that the latent energy thus set free may cause physical changes of such dimensions as to be dangerous. Data concerning the capabilities of an oil switch is only obtained by tests and research work, and such tests and research work carried out on any particular design are not of any substantial value in their effect upon other designs whose details and principles

are not identical. A series of tests made with the aid of the oscillograph follows, showing the effects on the current and potential waves caused by the rapid opening of the electrical circuit. These records serve to demonstrate phenomena not hitherto understood, and the variety of the results can be seen by comparison of the records.

Kilowatt Capacity.—The most important section or link in the transmission is the oil switch and its controlling features. Many precautions are taken in the way of introducing elements external to the oil switch to protect the latter from failure. Apart from the current and potential rating the kilowatt capacity should be known. This kilowatt capacity again is affected by the position of the wave on opening and the power factor of the circuit ruptured. An oil switch which may satisfactorily open a 10,000 kilowatt load at unity power factor, will entirely fail to interrupt the circuit successfully on a smaller load at a power factor less than unity. The fact that a " potential " exists to restore the circuit, when the current is zero, imposes an extremely severe duty on the switch. It is quite common for engineers to state that this or that switch will satisfactorily open a stated kilowatt capacity without any allusion to the power factor or the position of the wave on opening. Again, although the switch may open a predetermined load, and has been subject to tests to demonstrate its qualities, other conditions may arise that were not known when considering the question, such as " the inductance and the capacity of the system," " Resonance," " High Harmonics," which all play their part in the release of an electrical disturbance. With the continued growth of supply undertakings these conditions become more severe and the duty is thereby increased. Hence, apart from the existing conditions of the supply, margins must be allowed for these contingencies.

Rise of Current Increment.—The severe duty of a switch can be imagined when it is realized that on a short

circuit test of a 5,000 K.W. generator the current increment rise is at the rate of 850,000 amperes per second. Clearly the rapidity with which an electrical circuit is opened is a point of great importance, because, apart from the fact that the rapid opening of a circuit having appreciable inductance may lead to excessive pressure rises, it must not be overlooked that if a short circuit can be disconnected before the current can reach a dangerous value the rise of pressure may not be excessive even with a rapid break. Instances, however, are known where the pressure has quadrupled across the break of the switch with a rapidly rising current.

Internal Reactances.—In order to limit the destructive effects of instantaneous short circuit current, internal reactances have been introduced in the generator windings which naturally affect and are at the expense of regulation. If, however, the generator breaks down, the short circuit current which can flow into it is only limited by the internal reactance of the other generators operating in parallel with it.

External Reactance.—These artificial devices have been introduced to limit the maximum instantaneous value of a short circuit. The principal drawback to their use is that a potential builds up across the reactance on short circuit, and when interrupted appears across the switch blades where its energy is more persistent than if the generator were short circuited. The presence of reactance modifies the power factor of the circuit and imposes an infinitely more dangerous condition on the circuit under rupture. Thus when the current is zero, the potential is a maximum, so that when the electro-magnetic energy is a minimum the potential is a maximum, tending to restore the circuit by puncturing the insulating medium between the contacts.

Reactance in Alternators.—The introduction of internal or external reactances for limiting the value of a short circuit current introduces a more complex study than self-inductive armature reactances. The maximum

short circuit current of a single unit with self-induced reactances is :—

$$Im^{\circ} = \frac{Em^{\circ}}{z}\left(I + e - \frac{r}{x}\pi\right)$$

This equation shows that the short circuit current does not increase in proportion to the number of units in parallel and that maximum current occurs at zero potential, the torque varying inversely as the reactance, causing stresses and the dislocation of the system on which it takes place. To compensate for torque and excessive strains under short circuit, the reactance, if applied, should not exceed ·15 per cent. per phase equally distributed. The generally accepted theory of short circuit alternating currents is that they are limited by the armature reactance and self-inductance; that is, the current in the armature represents the M.M.F. which, with lagging current at short circuit, is demagnetizing or opposing the impressed M.M.F. of field excitation, and by combining therewith in a resultant M.M.F. reduces the magnetic flux from that corresponding with field excitation and armature reaction; this in turn reduces the generated E.M.F. from the normal e° to a virtual E.M.F. e^{1}. The armature current also produces a local magnetic flux in the armature iron and pole faces which does not interlink with the field coils but is a self-induced flux, and is therefore represented by a reactance x_1, combined with the effective resistance r^1 of the armature winding, thus giving the self-inductive impedance.

$$Z_1 = r^1 - Jx_1 \text{ or } Z_1 = \sqrt{r_1^2 + x_1^2}$$

At short circuit current the virtual generated E.M.F. e_1 is consumed by the armature self-inductive impedance Z^1. As the effective armature resistance r^1 is very small compared with its self-inductive reactance x_1 it can be neglected.

The short circuit current of the alternator in permanent condition is—

$$i = \frac{e^1}{x^1}$$

or, as the armature reactance may be represented by the equivalent or effective reactance x_2 and the self-inductive reactance x^1, the effective reactance of the armature reaction x_2 combines to form the synchronous reactance x_0.

$$x_0 = x_1 + x_2$$

Therefore, the short circuit current of the alternator can be expressed in permanent condition

$$i = \frac{e^0}{x_0}$$

$e^0 =$ normal generated E.M.F.

There is no doubt that internal reactance decreases the physical strain in the end turns of generators and the introduction of external reactances introduces additional strains on the end turns of windings. Their use however, in the author's opinion, is not advised, as the safeguards secured in this manner introduce greater evils on the system which are detrimental to continuity of supply. While it is easy to provide adequate protection for the generator windings, it is a far greater problem to provide switchgear or other rupturing devices that will satisfactorily deal with a distorted current or potential wave. As, however, the success of a supply is dependant upon such provision, and strains due to shorts on internal windings should be considered apart from the value of regulation, the switch designer should not burden himself with any save the economic considerations involved.

It must be realized that an oil switch does not depend upon oil circulation, but has to deal with the explosive forces developed in the region of the break and their conversion.

Time-delayed Switches.—In many cases time-delayed switches have been advocated for the reason put forward—that such a switch opens circuit after the period of maximum disturbance. If it is known that the disturbance is of short duration, and that such a disturbance will not damage the system, and the destructive effects appear only in a fraction of time, then the protection of the switch is assured. It would seem that such a disturbance cannot be accurately gauged, hence the indeterminate quantity must be dealt with before it assumes a destructive force of high degree. The chief recommendation of the time-delayed switch is on economical grounds, but if the result be a switch that will not deal satisfactorily with the severe conditions met with on the system, this is false economy, and the liability of breakdown is increased. Again, dependence upon the positive action of a small link, which is in most cases far from robust, is obviously incorrect, as apart from the time element of such device and its characteristics, considerable doubts are manifest as to its selective ability. As before stated the switch should relieve a dangerous condition as quickly as possible, and the ill-effect of rapid opening is more than counterbalanced by the result of a rapidly rising current if left unchecked.

Short-circuit Currents.—Fig. 12 is an oscillograph record of the effects of short-circuiting a 3,000 K.W. generator with a current increment rise of 850,000 amperes per second

$$\frac{X^1}{Y^1} = \text{rate of change of current.}$$

The actual current can be calculated from the characteristics of the machine as shown under "reactances." The current may vary between twelve and twenty times its normal full load output. If this be known the current depends upon the time taken by the switch in opening. Thus, if the opening be delayed the armature reaction

of the machine becomes effective, thereby dropping the volts and lowering the amperes at break. This does not suggest that time-delayed switches are correct, as the switch is primarily for the protection of the system, not of itself, and the ill-effects are shown and dealt with in another portion of this book. Apart from the fact that a machine will stand a rising short, or whatever its reactance is, arcing under oil produces heavy oscillations which not only assist in fracturing the insulation but distort the system considerably. Mathematical conclusions on this point are dealt with, and it will be seen that the quicker a

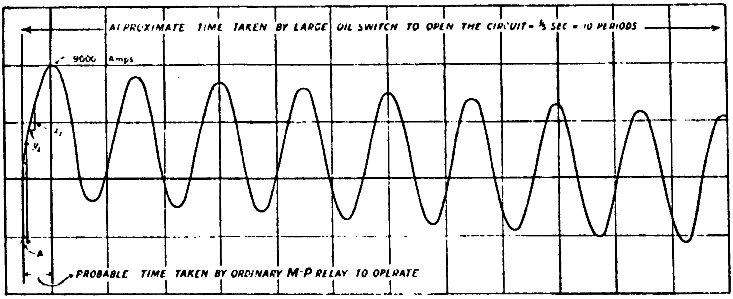


FIG. 12.—Key Oscillograph of A.C. Generator Shorts.

short is relieved the better. The estimated value of a short on an American station of 50,000 K.W. capacity at 6,000 volts was 240–600 amperes per phase. This figure was arrived at by taking an actual test on the same station of a much smaller capacity, pro rata. A mental calculation will show the ultimate capacity of the switch designed for a feeder of 200 amperes in dealing with the full load short-circuit current of the station behind it, say at 40 per cent. P.F.

Conservation of Energy.—Energy cannot be consumed, but may be converted into another form, hence the production of heat by concussion. Every charge of electricity has its equal or opposite charge somewhere more or

less distributed, the sum of the negative being equal to the sum of the positive charges. It is therefore possible to convert the accumulative energy of the destructive forces of short circuit in the same manner as we can transform "latent energy" into "kinetic energy" and reduce those of different degrees to "energy" of the same degree. For example—the sun is a source of "kinetic energy" of high degree and coal a source of latent energy. The burning of coal serves to transform latent into kinetic energy and the cooling of the sun will illustrate the lowering of degree of "kinetic energy." Thus if it is possible to transform the accumulative energy of an electrical disturbance after nature's method we approach the solution of our switching problems. The author submits, *absit dicto invidia,* that he has succeeded in designing a switch, opening in a new di-electric which goes far towards a solution. The chief feature of this new di-electric is that it can be graded so as to prevent any predetermined rise of current, with the same gradient for potential rises, and it is practically uninflammable. Thus, the arc on rupture does not vaporize it, its specific gravity is 0·79, viscosity unchangeable under 230° F. in comparison with boiling water under one atmosphere 212° F. While it is not proposed to devote much attention to this innovation, it serves to show that energy may be converted without destroying the stability of the system. It has been proposed to dissipate this energy as heat by the introduction of resistances across the break of the switch. Apart from the impracticability of such a suggestion, the destructive effects would be greatly increased, seeing that the power factor of the system is modified, and moreover the dissipation of forces would not take place at the time of maximum stress. It is an old suggestion and was applied on the Continent to a Swiss scheme. After trial the resistance was removed with marked advantage.

Interchangeability.—Oil switches fixed on a main

switchboard should all be of the same size, and of equal rupturing capacity. To instal switches of smaller dimensions on the feeders than those on the generators is obviously incorrect, as each switch must be capable of dealing with the full capacity of the station. In addition there should be complete interchangeability so that one standard set of spares will replace any defective parts of the board. Economies can be effected in the design of the switch by

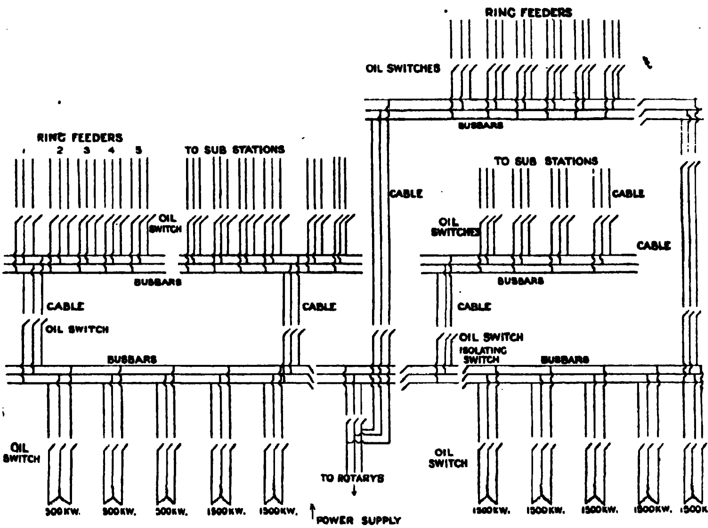


FIG. 13.—Diagram of Operations in taking A.C. Oscillograph Tests.

adopting forced arc damping gear. This apparatus is reserved for switches for high potentials.

"Oscillograph Records of Tests on A.C. Switches."—The following tests were made on a 20,000 K.W. station, 25 cycles at 5,000 volts. (See diagram, Fig. 13.) The steam sets were run up for their full delivery before the tests were taken. For the limiting short tests an oil switch was closed, placing such sets as were then on load on short-circuit across phases with a limiting resistance capable of absorbing 10,000 K.W. The limiting resistance was of the metallic type.

Between the resistance and the supply station there was a 3-core cable 0·15 square inch section, 1,000 yards long, having an impedance of 2·4 ohms. As far as the tests were concerned the system was entirely insulated, thus the return path for the current was through either of the phases. The potential coil of the oscillograph was connected across the phases and was changed over from one to the other as a precaution against any variation in pressure. The operating coil of the oscillograph was in circuit with the secondary of a potential transformer, ratio 50/1, the current coil of the

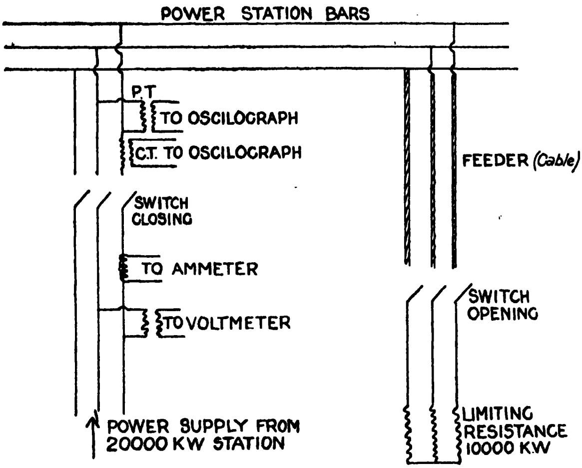


FIG. 14.—Diagram of Limited Shorts.

oscillograph being operated by the secondary currents of a transformer whose primary was in series on one of the phases, ratio 30/1. The effective results were obtained by calibrating the oscillograph by means of direct current impulses. Instantaneous values are not given but can be obtained by calculation. The definition of effective currents in the calculations are :—

Continuous current $\sqrt{\text{mean square of alternating current}}$

" P.D. $\sqrt{\text{" " " " P.D.}}$

Fig 14. Diagram of connexions of limited shorts.

Test 1 (Fig. 14a). The effects produced on opening the circuit with sets on load equivalent to 7,500 K.W. at 5,000 volts. The switch contacts moved under gravity in a vertical plane, assisted by springs under tension, an arrangement which in comparison with other switches appears to give the most favourable results. The speed of the switch contacts was 70 feet per second. The time duration of the arc was 1½ periods at 25 cycles per second, a current rise of 2,040 amperes on the first wave, and 1,800 amperes on the last half period. Rate of rise approximately 250,000 amperes per second. Practically no distortion of the wave appears.

Test 2 (Fig. 14a). Gives the result of opening the circuit under the same conditions with a time-limit switch. The complete rupture occupied 6 periods of the wave. Rise of current on the first wave was 2,040 amperes, which diminished to 1,200 amperes on the last wave, rate of rise of current 250,000 amperes per second. The potential apparently increases as the current diminishes, maintaining a potential across the break when the current is zero. Had this not occurred the arc would have been damped out earlier.

Test 3 (Fig. 14a). Another test under similar conditions to (2) with a time-limit switch which cleared the circuit in 7 waves. The waves are not so pronounced at their maximum as in the previous tests, and there is less distortion. The rise of current in the first wave was 1,500 amperes, and in the second 2,060 amperes, gradually declining to 1,440 amperes in the last period, the distortion of which is the result of the current endeavouring to establish itself. Rate of current rise was 450,000 amperes per second.

Test 4 (Fig. 14b). Taken with a switch having a velocity of 60 feet per second. Current started to flow at the peak of the voltage wave, the circuit being opened in 2½ periods or $\frac{1}{10}$ of a second. It is noticeable that in

this test, as in others, the current at final rupture appears on the other side of the zero position, the voltage at this instant being unable to pierce the di-electric. The rate of current rise reaches 300,000 amperes per second. The total

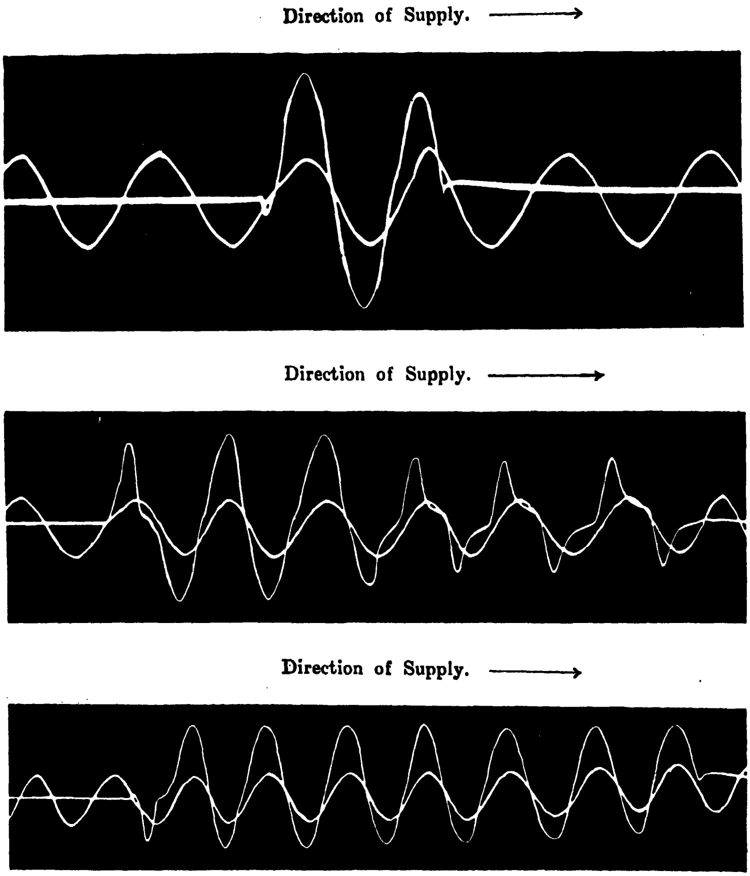


FIG. 14A.—Tests 1–2–3, Oscillograph Effects of A.C. Shorts.

rise on the first half wave was 1,560 amperes, second wave 1,920 amperes, with very little diminution on the succeeding waves. As the switch had a 5-in. break the time occupied in opening was $\frac{1}{14}$ part of a second. The

switch, therefore, was fully opened before the circuit became entirely disconnected.

Test 5 (Fig. 14b). No. 4 repeated. The same values and results appear except the time of clearing the circuit.

The following series of tests differs from the foregoing in

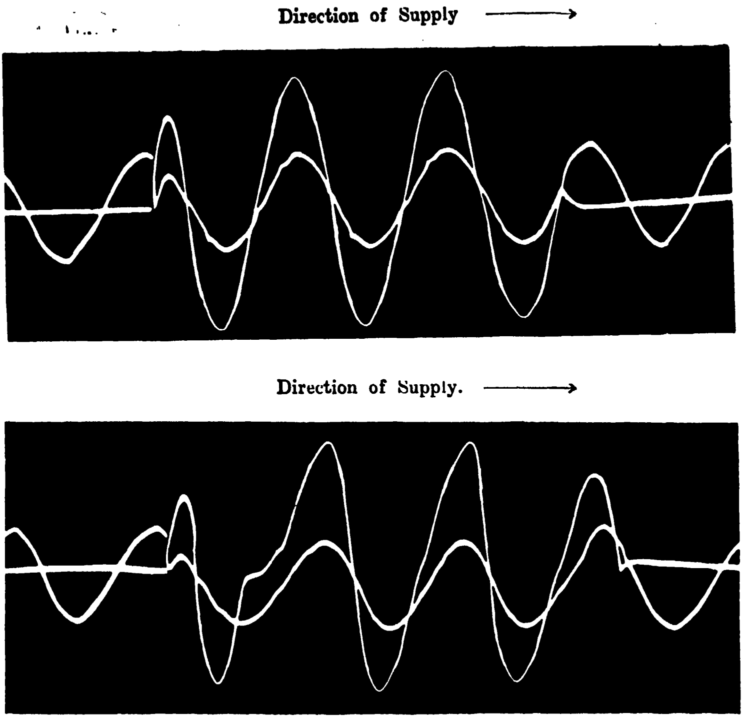


Fig. 14b.—Tests 4–5, Oscillograph Effects of A.C. Shorts.

that it shows the result of opening and closing long feeder circuits.

Fig. 15 is a diagram of connexions for these tests.

Test 6 (Fig. 15a). Illustrates the closing of a 5-mile feeder which consisted of a 3-core 0·15 square inch cable connected through various sub-stations, the impedance being 0·69 ohm. per phase. It has been stated that the closing or

opening of unloaded feeders gives rise to excessive pressures. In considering these records it should be noted that the

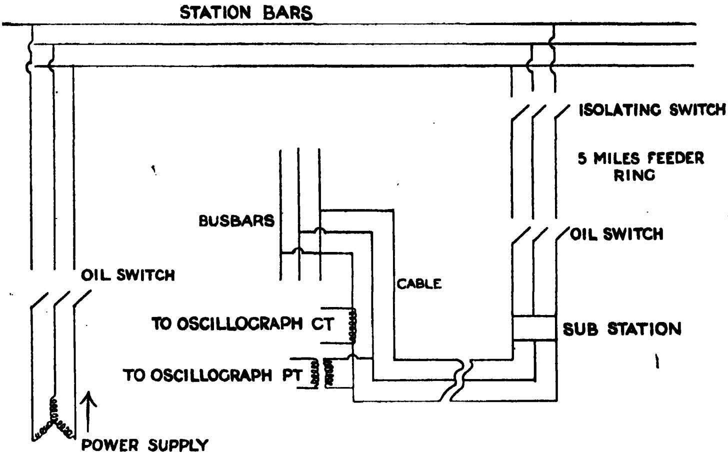


FIG. 15.—Diagram of Connexions on Long Feeder Tests.

transformer primaries were disconnected; if connected, and with open or closed secondaries, the results would have been far different. The maximum rise in this case was 14,000 volts, quickly assuming the normal instantaneous pressure of 8,000 volts between phases.

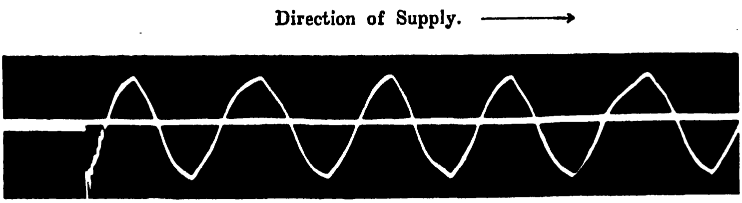


FIG. 15A.—Test 6, Oscillograph Tests on Five Mile Feeder.

TEST 7 (Fig. 15B). Test No. 6 repeated under same conditions; the rise of voltage due to closing was 16,000 volts. Normal instantaneous pressure, 8,000 volts.

TEST 8 (Fig. 15B). Test No. 7 repeated, showing a 12,000

volt rise, the normal potential being 8,000 volts instantaneous rating.

TESTS 9–10–11 (Fig. 15C). These tests show the effects on the same circuit of opening under no load, the pressure rapidly approaching zero. In the case of Test 10, 3,000 volts remained on the circuit one-fifth of a second after opening, the voltage finally reaching zero in a quarter of a second.

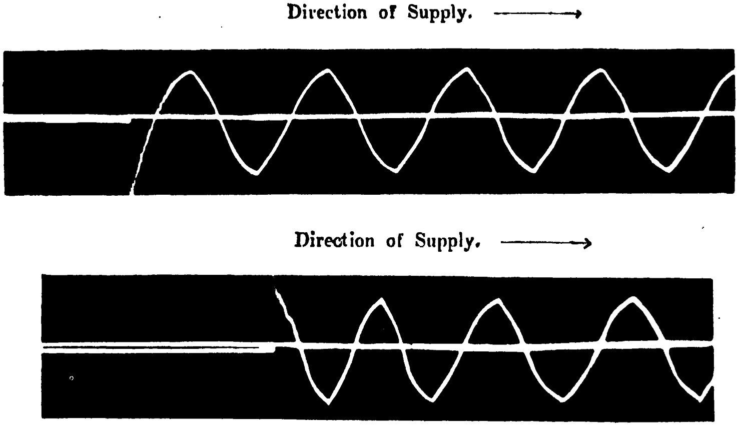


FIG. 15B.—Tests 7–8, Oscillograph Test on Five Mile Feeder.

TESTS 12, 13, 14, 15 and 16. The series of records on repetition of Tests 1 to 5 inclusive, which were taken on the power station side, with the automatic switch relieving the short, adjacent to the limiting short resistance at the extreme end of the feeder. In these latter tests the records were taken with the automatic switch opening on the power station side. The current in the case of (13) reached 2,160 amperes, normal voltage being 5,000, three current waves passing at the time of opening, and the last wave reaching 1,800 amperes. Irregularities appear in the waves lasting $\frac{1}{75}$ part of a second, due to the variation of movement of the three phases of the switch. It is practically impossible to make a switch in which all three phases leave

contact at the same instant. Irregularities in the other records are due to the same cause.

Pressure in Oil Tanks. Tests have been made to ascertain the pressure on the sides of the oil tanks resulting from opening predetermined loads and shorts. A pressure of 60 lb. per square inch in 0·11 second was obtained by

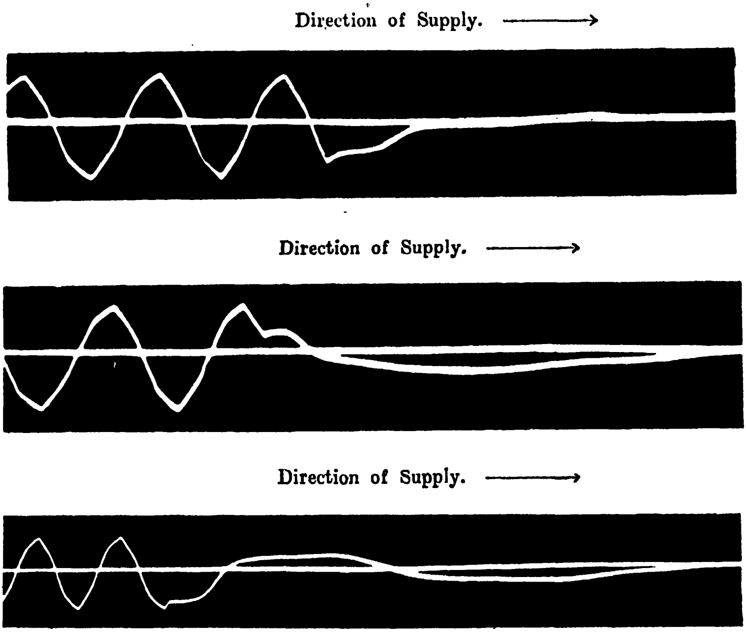


FIG. 15C.—Tests 9–10–11, Oscillograph Test on Five Mile Feeder.

shorting a 12,000 kilowatt, 9,000 volt, 25 cycle generator. A pressure indicator equipment is shown in Fig. 16, constructed on the same principle as that used for hydraulic tests on the Continent. The instrument was fitted with a pointer which remained in its maximum position at the instant of opening. The operating disc was placed in the position of maximum disturbance of the oil. The resultant forces as observed through the transparent sides of the oil tank were in a direction at right angles to the flow of current. On

a 15,000 K.W., 6,000 volt short the pressure appeared to be 110 lb. per square inch. The tests were repeated to ensure accuracy, and the results are given in the following table. It is of note that the pressure in lbs. per square inch is greater at the lower than with the higher pressures.

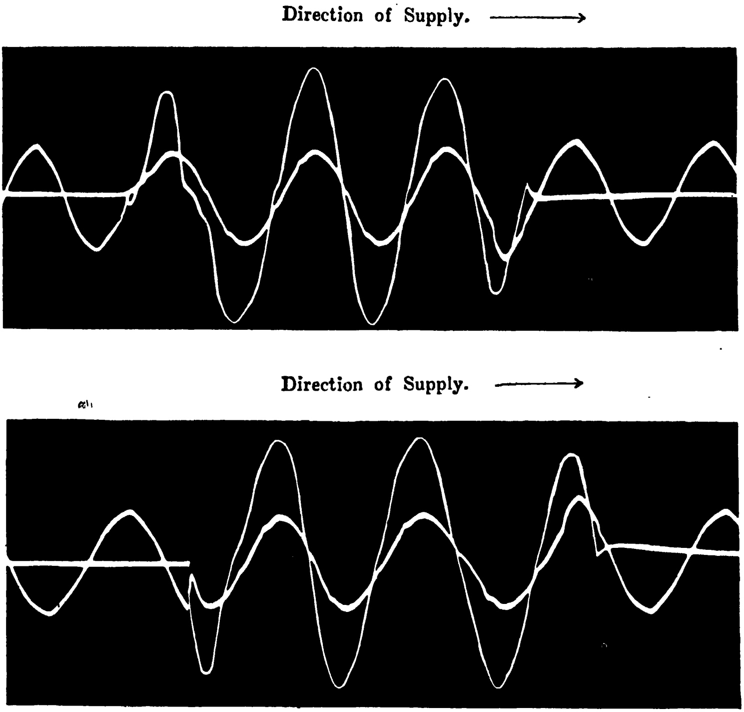


FIG. 15D.—Tests 12–13, Oscillograph Test of Limited Short A.C.

Amperes.	5,000 volts A.C. lbs. per sq. in.	2,000 volts A.C. lbs. per sq. in.	500 volts A.C. lbs. per sq. in.
700	41	41·6	43
1,000	40·5	42	44·7
1,500	40	42	47
2,200	46	46	49

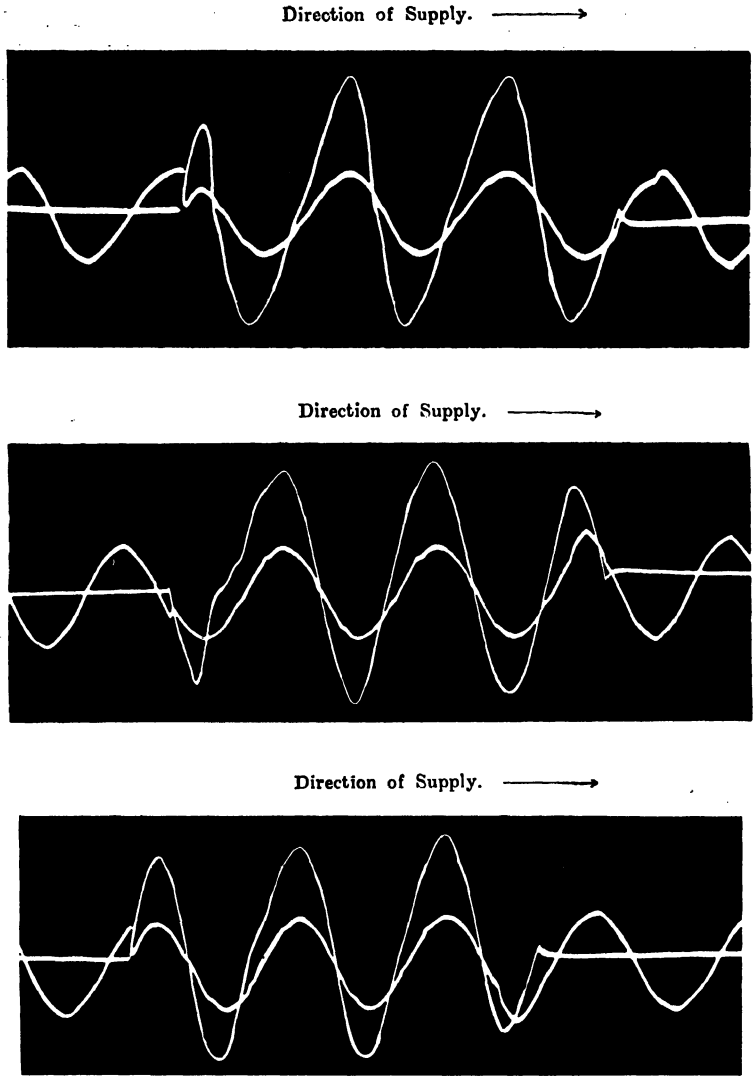


Fig. 15e.—Tests 14–15–16, Oscillograph Test of Limited Short A.C.

In order to decrease the strain on the switch tank a three-ply wood lining, which is fitted primarily for insulating purposes, is so placed inside the tank as to leave a space between it and the sides, of from $\frac{3}{8}$ to $\frac{5}{8}$ inch. The result is, that when the oil under rupture is set in violent motion, the layer of oil between the lining and the tank is quiescent, thus tending to damp out the shock. Again the lining breaks the force of the operation, acting as a buffer between the contacts of the switch and the tank. The tanks must be so made that the oil cannot splash or blow out

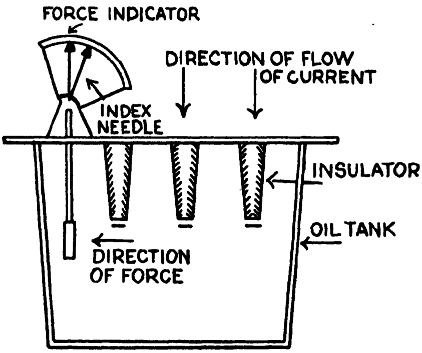


FIG. 16.—Method of Force Measurement.

of the tank. If the tanks are made oil tight, provision must be made for the escape of gases. Gases generated on rupture are liable to explode violently with such pressure as to burst the tank. There are many ways of coping with these problems, and their choice depends upon the principles governing the action of the switch. When currents assume large dimensions, or if frequencies be low, the iron frame of the switch should be so constructed as to prevent heating due to eddy currents. The frame may be in two parts, or open between phases, to prevent circulation of eddy currents. The direction of flow of current through the switch must be the same in all three phases, otherwise assuming the circulation of eddy currents

to be permitted, these will not neutralize one another, but all three act in unison.

Insulators were formerly of the corrugated pattern designed principally to increase the insulating surface for a minimum height. It has been found in actual practice that the insulation is decreased by these corrugations, as they accumulate dust and moisture, ultimately serving as a conducting path. It is now standard practice to provide insulators of the straight pattern. Apart from other qualities these are easier to clean and cheaper in construction. Porcelain does not appear to have been replaced by any other insulating material for this work. Vitrified porcelain is specially moulded and treated by several processes, such as glazing and extra firing, in order to withstand excessive electrical pressure. It consists of "Kaolin," "Felspar" and "Quartz," the combination of which, if properly fired, produces a "crystalline silicate" which when glazed is capable of withstanding very high pressures. The method of fixing these insulators to the switch framework is by clamping, not by cement, as cracking under contraction and expansion necessarily follows.

Switch Breaks.—Except for extra high pressures the blade of the switch should move in a vertical plane for the following reasons :—

(1) This movement involves minimum displacement of oil.

(2) Movement is assisted by gravity, and speed of opening is thus a maximum.

(3) The effects of rupture are concentrated in a vertical plane, and not distributed through the tank as is the case where the movement is axial. For voltages of 4,000 and upwards and for currents above 150 amperes each phase of the switch should be in a separate tank or the latter fitted with three-ply wood lining between phases. The length of break of an oil switch should not be less than 3½ in. for 2,500 volts, 5½ in. for 5,000 to 6,000 volts, and

8 in. for 10,000 volts per pole, per phase, the actual length per phase being double the above figures. The figures given above do not include the range necessary for bringing the contacts under tension, but refer to the distance between the fixed and moving contact in the "off" position.

Switch Contacts.—The main contact brush of laminated pattern represents by far the best practice. As the pressure acts in a direct line with the toggle mechanism, it conduces to speed in opening, the pressure being also assisted by gravity. Again, the contact area is a maximum in relation to its current density. The contact area of a copper bar (unlaminated) must be approximately five times the sectional area of the bar with 25 lb. pressure per square inch to ensure the same conductivity as if solid. Increasing the pressure to 35 lb. per square inch gives the same result with a contact area of only 4·2 times the sectional area. The contact area does not vary inversely as the pressure. This question, however, must not be disregarded, as it affects the potential gradient of the contact. A contact immersed in oil has twice the conductivity of a similar dry contact and is always at maximum efficiency, as under oil there can be no oxidization of the metal. The conductivity of a dry contact decreases from day to day; oxidization is at work, constantly impairing the electrical efficiency of switchgear exposed to the action of the atmosphere. The face contact of the laminated brush is cross-cut, giving maximum area at this point, and all main contacts should be provided with auxiliary sparking tips, which are called upon to finally rupture the circuit on opening. Wedge and cone contacts are not so efficient as the brush form, from the standpoint of conductivity. The pressure is not in direct line with the operating mechanism, being in a direction diagonal to the toggle and may, due to guide friction, give a total frictional resistance more than equal to the weight of the switch, thus causing the latter to hold in after the toggle is released.

Character of Di-Electrics.—The term "Di-electric" is used to signify a substance, the various parts of which, after an electrical disturbance, may remain, without any process of readjustment and for an indefinite period, at different potentials. There is so far no perfect non-conducting "Di-electric." Di-electrics are capable of assimilating an electrical charge, and in theory consist of "ions" (charged particles), which in turn embody "Atoms" or combination of atoms and of infinitely smaller negatively charged particles called "Electrons." As "Atoms" contain "Electrons," the former can assume aggregate negative charges, which are normally balanced by the positive charges; it follows that the addition or removal of one or the other charge leaves either a positive or a negative "Atom." The amount of energy necessary to distort the Di-electric is proportional to the number and velocity of these "ions"; in metals which are of high conductivity, the current increases with the pressure applied, because the resistance is constant. In Di-electrics this only applies when the conduction is due to the initially free ions, the resistance decreasing when the energy is intense enough to effect the liberation of the ions.

Test of Di-Electrics. Fig. 17 records the breakdown voltages between needles immersed in oil. One curve relates to a new di-electric introduced by the author. Further reference to this di-electric does not come within the scope of this book, except that it is used only on systems where the pressure exceeds 20,000 volts. The question of thick or thin oil is determined by the use to which it is to be put. Sedimentation is a very undesirable feature, and the presence of carbon particles lowers the insulation. Tests should be carried out to determine its flashing point, which should be as high as possible, and no moisture should be present. The viscosities of the oil at various temperatures should be known and duly considered in its bearing on the action of the switch. Many oil troubles present

themselves, and those due to viscosity are not the least of these. Rupturing capacity of the oil switch, discussed under various headings, is, for instance, affected by the viscosity of the oil. Oil with a viscosity of 60° will not damp out the arc so effectively when at a higher temperature. Thus we find the temperature of one power house 90° F. and of another, 120° F., which again modifies the arc damping fluid. For extra high potentials the fluid is forced on to the contacts in order that the ebullition

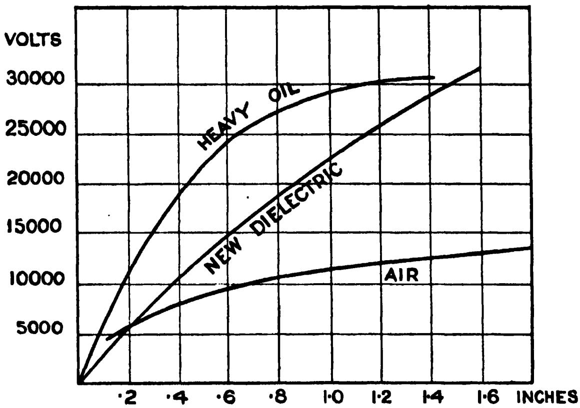


FIG. 17.—Test of Breakdown A.C. Volts.

of the oil may not be concentrated, and thus damping out the arc with oil of a more quiescent character. The arc is not ruptured in the time taken by the switch in passing to its maximum " off " position, as is seen by the foregoing tests. Thus, the oil has to effectively deal with this rupture. Thin oil is used for extra high potentials, and thick oil for heavy currents. One of the most difficult problems, however, is to provide oil suitable for the local conditions of service. Thus the oil for switch in a cotton mill has a higher viscosity than that used in colliery work.

Generally speaking, the arc should be formed near the head of the oil so that the gases may be released without

disturbing the mass of fluid in the neighbourhood of the break. The release of such gases should be provided for on the switch frame. On one of the latest designs for extra high potential service it was noticed that a gas release was provided in the form of an air duct attached to the plates that force the oil through the arc. This is quite an experiment, and its efficiency has not been demonstrated. Suffice it that some such release is needed. Having dealt with the general principles underlying the construction of the switch, there remains only its practical application to consider. In this connexion, as there are so many varied applications, no hard and fast regulations can be given, and its adoption is at the discretion of the engineer when the conditions are known. Switches for extra high potentials enter a totally different sphere of design, the latter having to cope with the abnormal conditions incidental to such service. For instance, breaks operating in a vertical plane have been advocated, but would be totally unsuitable for this special work, which necessitates a horizontal break, the switch blades moving in a horizontal plane, under a heavy head of oil. Hence the necessity of providing for the release of gases as explained before. Such a switch is provided with a multiple break. The question of insulation, etc., affects the design, and a few examples will show the need for special precautions in this class of switchgear.

Condenser Terminals.—The main lead insulator is of the condenser form of construction, being built up on equipotential lines so that the complete strain is distributed over its area. Additional data underlying its construction will be found under "Insulation for High Potentials," which deals with the E.M.F. of aerial transmissions and cables. The strains of such form a basis for theories connected with the condenser terminal, which was originally constructed as the result of experiment. The following equations bear a distinct resemblance to those used in connexion with

insulated cables. If a di-electric is absolutely homogeneous, each portion will bear equal strain. Tests recording the effect of dividing the di-electric into a series of condensers by the introduction of metal plates show that each condenser in series will take its share of the strain in inverse proportion to its capacity. A condenser terminal can be constructed by utilizing a rod in the centre to carry the current, having its ends tapered off in steps, with a series of condenser plates surrounding the insulation. The end layers determine the distribution of voltage over the surface. The equation for two concentric cylinders is—

$$C = \frac{K\ l}{2 \log \frac{r^2}{r^1}}$$

C = electrostatic capacity.
K = specific inductance of di-electric.
l = length in cm. of conducting cylinders.
r^1-r^2 = radius in cm. of inside and outside conducting cylinders.

It will be seen that the capacity can be varied at will by changing the inductance or thickness, length and distance between the conducting cylinders. Terminals may be constructed of metal tube and mica, shellac forming the binding material. At regular intervals a layer of tin foil is inserted. Thicknesses of steps must be uniform, and air spaces or any irregularities will introduce static effects. The edges of the tinfoil exposed to the air should be bevelled.

Square edges give rise to a potential above earth which may enhance corona effects. If the terminal itself is immersed in oil, the edges of the tinfoil are of little consequence, since the oil is practically unaffected by corona. This form of terminal is far superior to the porcelain insulator in that cracking is entirely eliminated, and discharges due to unequal potential and leakage strains are entirely

eliminated. This form of insulator renders commercially possible voltages exceeding 50,000 without the ill-effects attendant upon the standard design when used with such high pressures.

Corona Losses.—Corona effects are proportional to the frequency, the square root of the conductor radius r, and the excess pressure above critical volts e^1. The critical disruptive voltage is found by the equation—

$$e_1 = m_0\ g^\circ\ r\ \log_e \frac{S}{r}\ \text{K.V. to neutral.}$$

$g^\circ =$ disruptive gradient of air in kilo-volts per cm. at 25° C.

S = distance between conductors in cm.

r = radius of conductor.

m_0 = constant of conditions of conductor.

The critical voltage is considerably higher than the disruptive pressure and varies according to the size of the conductor.

The visual critical voltage e^2 is derived from the disruptive gradient g° by equation—

$$e^2 = m^a\ g^\circ\ \delta\ r\left(1 + \frac{0{\cdot}301}{\sqrt{r}}\right)\ \log_e \frac{S}{r}\ \text{K.V. to neutral.}$$

m^a = conductor corona.

δ = barometric pressure.

The above equations can be amplified to various degrees by the introduction of wind pressure, etc., these, however, serving the basis of further equations for local conditions. There is practically no limit to the deductions that can be made, and theory has now combined with practice, so that we are able to judge and calculate such effects and to provide means whereby they can be neutralized. Corona always takes the direction positive to negative, and is vibratory in character. The condition of the atmosphere obviously modifies various calculated results, but normally

the volts per inch of air-gap necessary to produce rupture are—

$$\frac{170{,}000 \times 10^{13}}{2{\cdot}244 \times 10^{13}} = 75{,}700 \text{ volts},$$

which is in accordance with leading physicists' deductions, their estimated value being 76,000 volts on conductors from 0·65 in. to 0·2 in. Beyond the surface of the conductor 0·65 in. in diameter, the normal atmosphere broke into "corona" at a distance of 0·07 in. At the di-electric flux density of $170{,}000 \times 10^{13}$ coulombs per inch cube, the coulombs per inch cube per volt established in the normal atmosphere are $2{\cdot}244 \times 10^{13}$. It might be here mentioned that the corona formed on the end of tin foil electrodes are accentuated by the presence of nitrous acid.

Insulation for High Potentials. — Maxwell points out: "If the electromotive intensity at any point in a di-electric is gradually increased, a limit is reached at which there is a sudden electrical discharge through the di-electric. The electromotive intensity in a di-electric, when this takes place, is a measure of the electric strength. This is known as 'Electric strength of di-electric.'" The equation governing a charged cable surrounded by concentric layers of insulation is—

$$F = \frac{2\,Q}{\epsilon\,\rho}$$

ϵ = specific capacity of the di-electric section.
ρ = distance from the axis of cable to this section.
Q = charge per unit length.
The equation of the electrical stress is therefore—

$$F = \frac{Vu}{\rho ln\,\frac{r^1}{r^2}}$$

Vu potential between conductors and sheath.
r^1 radius of cables.
r^2 radius of conductor.

For practical purposes the equation may take this form—

$$K = \frac{0{\cdot}434\ V}{r\log\left(\frac{T + r}{r^1}\right)}$$

which equation may be used to calculate the thickness of di-electric to insulate a wire of known radius. The equation is modified due to the irregularities of induction. A well-known authority points out that the use of stranded cable increases the stresses by a factor of from 1·2 to 1·5 according to the class and thickness of layer. The figure K replaces F, the latter being based on the assumption that the lines of electrostatic induction extend radially between the conductor and sheath; its density, therefore, is greatest at its surface; K, therefore, is the maximum of F.

In the use of extra high potentials it is necessary to understand the phenomena of the electrostatic field which is partially dealt with under "Surges and Oscillations." The clear conception of such opens up a field of equi-potential insulation for oil switches and transformers. The choice of cables and their gradient voltages, together with electrostatic quantity and intensity, must be appreciated before efficient control can be applied on such transmissions. Cables break down due to lack of homogeneity in the insulating material and to the transient effects of over voltages. The gases generated by mechanical skin diseases and which form bubbles are the chief causes of such trouble, more so than the unequal distribution of strains in E.H.T. service.

In the early days deterioration of cables by formation of air holes was noticed. In those cases, however, the cable had been strained locally beyond its di-electric strength, by the secondary effects known to some engineers as "localized corona disturbances." Corona discharges in air are not the same as corona effects in confined gas, inasmuch as the latter are more persistent and sustained

by the chemical disintegration which accompanies breakdown. If a cable could be made on the same lines as the condenser type of terminal, we should open up a field in which tape and rubber have failed. If the insulation is strained by the formation of pin holes, the energy of the electrostatic field concentrates on the outer insulation. Dr. Steinmetz terms this "The Shearing Strain," a phenomenon which can be exemplified by placing a thin sheet of mica between a point and a plate. The mica sheet breaks down at a certain voltage. If we now place a small drop of oil on the point, the mica sheet breaks down at a much less voltage. Brush discharges spread from the point over the mica, and give a gradual slope to the potential gradient. The drop of oil by its much higher di-electric strength cuts off the formation of the brush, brings the localized voltage to bear on the di-electric, and the electrostatic strain cuts through at a much lower voltage. This phenomenon is guarded against by tapering the edges of the insulation at cable ends. When a breakdown occurs in a di-electric it means that in that broken-down space a current flows. What are the laws governing the current flowing in air or other gases, or in those materials which are used as insulating media? In solid di-electrics we find that the effective resistance is not a constant but a function of the current density, and has an enormous negative co-efficient, that is, the resistance increases enormously with decreasing current density approaching infinity or zero current. If a breakdown strength is exceeded at one point, the di-electric may be stressed beyond breakdown with no current flowing, since the current would be so small, and the resistance of the material so high, as to cause a higher potential than the normal gradient across that space. The breakdown must be large enough to reduce the resistance of the di-electric sufficiently to pass the current. The laws governing gas production enter a slightly different sphere, since they are based on the homogeneity in

the exterior, which homogeneity is consistent with the insulation of leading-in cables to oil switches, etc. The laws of "corona," and "potential gradient," however, apply in either case, and the condenser type of terminal is the result. Temperature affects the laws of resistance, however, and various materials have different temperature co-efficients. The various layers being at different temperatures the voltage gradient would be affected. The piercing values of direct and alternating voltage are not the same. Since, however, the voltage of direct current does not ordinarily enter the region of extra high potentials, comparative data would be of little value. Such results were published by the technical press in Vienna in 1911, however. The resistivity of cables was greater on extra high direct voltages and currents than under alternating pressures, the comparison being in R.M.S. values. The breakdown voltages of direct currents were approximately 1½ times those of the maximum A.C. voltages. In the case of porcelain insulators the corona or leakage path was effected at an average ratio direct to alternating voltage of 3 to 1. The following table gives the maximum voltages for which cables can be built by H. S. Osborne.

No. of Layers.	Insulation.	Rad. of Core m.m.	Circular mils.	Kilo volts.
1	All rubber . . .	12·9	1,030,000	78
2	All rubber . . .	6·85	290,000	112
3	All rubber . . .	4·29	114,000	132
2	Rubber tape . .	8·24	420,000	90
3	Rubber tape . .	5·59	194,000	115

The experiments in the laboratory, however, confirm these figures, which appear higher by 15 per cent. as far as kilo volts are concerned.

Surges and Oscillations.—There has been an element of mystery concerning the above in high potential trans-

mission lines, phenomena which are the result of setting free energy existing in two forms. Their intensity can be calculated from the line inductance and capacity, and from line impedance, voltage and charging current. There is energy stored in the circuit, or more correctly the system or part of the system which oscillates at low frequencies, and evidences itself in the form of surges which react on the whole system. Electric power can be considered the product of two factors: the quantity factor called current, and the intensity factor known as pressure or E.M.F. If electrical energy flows through a circuit it is continually being transformed, and the loss of energy is proportional to the product of the square of the current, and another constant of the circuit, "R." Certain phenomena accompany the flow of energy; the "Magnetic field" which exists in a direction concentric to the conductor, and the "Electrostatic stress" in a direction radial to the conductor; in other words the lines of Magnetic force surround the conductor, with the "Electrostatic force" acting radially. No energy is absorbed in maintaining this "Magnetic" or "Electrostatic" effect, but energy is necessary to produce them. When opening the circuit or converting the energy this fraction is returned to its source. It follows then that this condition can be instantly brought about, removed, or changed during a period we may call "Transient," and in which the energy of the "Magnetic" or "Electrostatic" field is altered, the actual time varying from one to several seconds, according to the amount of energy thus stored. As previously stated, the energy of the electrostatic field is proportional to the square of the current, and to a quantity "L" termed inductance. The "Electrostatic" field is also proportional to the square of the voltage and to the capacity, "C." An electric circuit also has resistance, "R," which is responsible for a certain loss of energy.

I^2R.

The loss due to inductance, "L," is represented by formula

$$\frac{I^2L}{2}$$

and that due to capacity, "C," by

$$\frac{E^2C}{2}$$

The opening of an inductive circuit results either in rapid dissipation of the stored "magnetic energy" rate or, alternatively, a high E.M.F. is induced. The magnetic energy, therefore, disappears with the current, and becomes "Electrostatic" energy; in other words the potential rises until the capacity, "C," has absorbed all the magnetic energy due to inductance.

There is of course some energy absorbed by the ohmic resistance; the oscillations, therefore, decrease more rapidly, the greater this resistance to current flow. The phenomena of surges and oscillations are thus analogous to the oscillations of a pendulum.

If "L" = inductance, "C" capacity, and "I" current,

$$\text{Magnetic energy} = \frac{I^2L}{2}$$

$$\text{Electrostatic energy} = \frac{E^2C}{2}, \text{ so that}$$

$$\frac{E^2C}{2} = \frac{I^2L}{2} \text{ or } E = 1\sqrt{\frac{L}{C}}$$

If E° = the full load voltage, I° the full load current, P the impedance of the line, and q the charging current, we have—

$$I^2X - P.C.^\circ$$

When X = 2 K. N.L. = the reactance of the circuit and N.N. its impressed frequency.

$$E^\circ K = q\, I^\circ K$$

When $K = 2\pi$ the equation is—

$$\left(\frac{P}{q}\frac{C^\circ}{I^\circ} = \frac{I^2 K}{E^\circ K}\right) \text{ or } \left(\frac{P}{Q} = \frac{E^\circ}{I^\circ}\right) \text{ or } \left(\sqrt{\frac{L}{C}} \text{ or } \frac{E^\circ}{I^\circ}\right) \text{ or } \left(\frac{P}{q}\right)$$

that is when full load current 1° consumes the voltage PC° the short circuit current (1) consumes the total voltage E°, therefore $1 = \frac{1^\circ}{P^\circ}$ and the line voltage of a short circuit surge we get equations, i.e.—

$$E = L\sqrt{\frac{L}{C}} = \frac{1^\circ}{P}\sqrt{\frac{L}{C}} = \frac{E^\circ}{P}\sqrt{\frac{P}{Q}}\ \frac{E}{E^\circ} = \frac{1}{\sqrt{\frac{P}{q}}}$$

the short circuit surge of the transmission line raises the voltage to $\frac{I}{\sqrt{Pq}}$ times the normal, where P is the impedance and q the charging current as fractions of the full load voltage E, the full load current I°P = 30 per cent. or 0·3, that is the impedance volts = 30 per cent. of the voltage, and E° impressed on the line. $q = 15$ per cent. or 0·15 of the charging current of the line, the equation is—

$$\frac{E}{E^\circ} = \frac{1}{\sqrt{0{\cdot}3 \times 0{\cdot}15}} = 4{\cdot}72.$$

The short circuit surges raise the voltage to 4·72 times the normal.

Earthed v. Unearthed Neutrals.—The design of switchgear and protective devices is considerably modified by the presence of an earth on the system. An earthed system imposes more severe strains upon gear than an unearthed system and more relays are required to protect it. As a precedent there are few supply undertakings and colliery transmissions in this country which have the neutral on the three-phase network earthed. There is a strong inclination to earth on extra high potention transmissions where surges and climatic conditions affect the system, and where it is desirable to limit the H.V. rises.

As far as safety is concerned, systems with an insulated neutral are preferable. A *résumé* of the advantages and disadvantages of both systems may prove useful.

Earthed Systems.—(1) For overload feeder protection on a three-phase system an automatic trip coil is required in each phase. Incidentally the use of three transformers, or—if the secondaries are connected in Z—three transformers and two trip coils. In the case of an unearthed system only two transformers with trip coils are necessary. The above system, therefore, requires additional links to protect it.

(2) If torque and the regulation of the generators are not exactly balanced the trouble due to interchange of currents between the sets is accentuated by earthing owing to the triple frequency terms in the E.M.F. wave.

(3) Magnetic and mechanical damage is a sequence of the heavy current rush following generator shorts, straining the whole system. To limit this, a compromise between the " unearthed " and " earthed " systems has been found, in the shape of a resistance or choking coil inserted between the mid point of generator windings and earth. Obviously if a resistance be inserted it must pass sufficient current to open all the circuit breakers. Thus if one breaker is set for 60 amperes, another, 600 amperes, and yet others for 1,000 amperes, the resistance must be capable of passing 1,000 amperes. The energy absorbed by such a resistance would be excessive and its proportions unwieldy. Again, in paralleling the generators the " earth " must be disconnected before synchronism is obtained. Choking coils are recommended by some engineers in place of resistance; we then get the effects of both capacity and inductance. The condition known as " Resonance " is therefore introduced if the " self-induction " and " capacity " are so proportioned that the current flowing when the capacity is short circuited, equals that flowing when the inductance is short circuited. Conditions can easily be assumed where " Resonance " could be obtained in respect to the eighth harmonic (nine times

the fundamental frequency); the inclusion of this choker will also produce a high potential between the system and earth. These drawbacks are well known, since it is the practice of engineers to insert relays and other protective devices to nullify their effects.

(4) Assuming the generators are solidly earthed, and a slight leak be present, the full potential is between that point and earth. In the case of leakage (temporary) down a coal pit, the attendant making the necessary repairs would, if he came in contact, receive the full potential, which might have serious consequences, whereas on an unearthed system he might remedy the fault with safety, as that portion of the system would probably be at zero potential.

(5) All gear used on "Earthed" systems must be of robust construction and highly insulated, as the electrical and mechanical strains set up by all earths and breakdowns are practically equivalent to short circuits.

(6) By having the "middle" earthed, arcing on rupture is more severe and of greater intensity than on an unearthed system.

(7) The principal advantage claimed for earthing is, that owing to the middle wire being at zero potential, the voltages between phases and earth are in conformity and cannot rise seriously above normal. Every "leak" or "earth" opens the circuit breaker more positively. If a flash-over due to lightning, or atmospheric discharge, causes the arc to puncture an insulator, this would result, as the neutral is earthed in a short circuit, and the supply would be interrupted; whereas, if the flash-over occurred on an unearthed system, the discharge, being only of temporary character and on one line, the voltage on the other two lines would rise momentarily to approximately double the normal, while the arc at the affected point is reduced as the voltage disappears.

Oil Switches for Direct Currents.—Particular interest attaches to the development of oil switches for direct cur-

rents. These were mainly designed to meet the conditions of underground work and to supersede the ironclad air-break switch which has been responsible for many failures in the past. The conditions underground, where firedamp or explosive gases are known to be present, are such that it is essential that all arcs formed on rupture shall be enclosed and kept out of contact with the atmosphere. So-called "gastight" Ironclad switches are produced, which consist of an air-break switch enclosed in an iron case fitted with rubber joints and so constructed that the arc cannot penetrate beyond the interior of the box. No matter what precautions are taken, however, it has been proved in use, that the gases cannot be kept out of the interior of this design. They percolate in time through the orifices of the case and explosions ensue. It is practically impossible to construct a "gastight" case. As the gases cannot be kept out of the case an "explosion proof" case has been designed, in which the presence of a "wide flange" joint ensures the arc formed on rupture being dissipated or damped out before it reaches the external atmosphere. As, however, these boxes are continually being opened for inspection, whilst dust and dirt abound, it is easily understood that in course of time apertures would be formed between the wide flanges affording the internal gases an easy path to the external atmosphere. Any arcing in such case would as easily fire a mine as if it took place on a switch of the open type, particularly as the external are lighter than the internal gases. If the arc could be ruptured in some fluid without any direct connexion with the exterior, the problem becomes easy. Hence the development of oil switches for direct currents. Engineers have fought shy of using this type of switch for D.C. service, and for two reasons: Firstly, the impression is widely prevalent that breaking direct currents under oil must cause an abnormal rise of pressure owing to the assumed rapid disruption of the current, and, secondly, because of the carbonization of the oil. If it

could be demonstrated that these drawbacks do not exist in fact, considerable progress in the construction of switchgear for D.C. supply would follow. As before stated, the oil preserves the conductivity of contacts as there can be no oxidization of the metal. The results of experiments shown by the oscillograph records are of particular value in this direction. It is not wise to rely upon the effectiveness of the oil to prevent any chance of ignition in a fiery mine through the agency of the oil switch. If there is a good head of oil over the contacts, as there should be, no doubt the risk is very small, but there is some vaporization of the oil at break, the gas rising in bubbles where liberated,

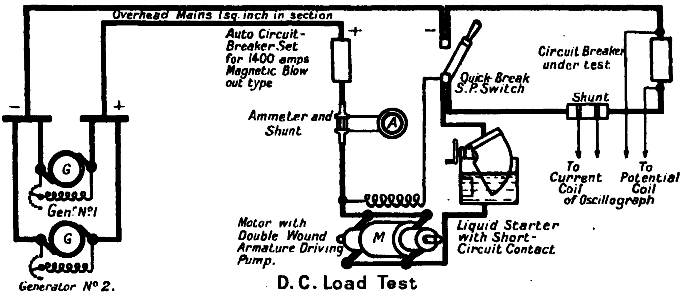


FIG. 18.—Diagram of D.C. Load Tests.

into the upper part of the case of the switch. The pressure in lbs. per square inch is greater on rupture of a D.C. supply than on opening a similar A.C. circuit. A table of the pressures per square inch is given under "Pressure in oil tanks," on A.C. work. A switch designed for A.C. work has only half the capacity if used on D.C. circuits. The pressure caused by an internal explosion of "firedamp" is not likely to exceed 200 lb. per square inch. Tests taken in Germany record a pressure of 105 lb. per square inch under arcing conditions. The tests recorded in this book will dispel the idea of danger due to rise of pressure, so that there remains only the carbonization of the oil. No doubt

more carbonization takes place with D.C. than with A.C. currents, but the presence of free particles of carbon in the oil does not measurably affect its high insulating quality. The deposit of carbon on the insulating media of the switch results in depreciation, but if the design of the fitting be such that there will be no tendency for the finely-divided carbon to be so deposited we approach the solution of the

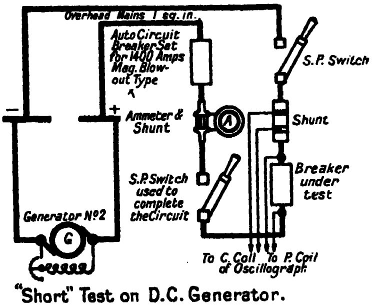


FIG. 19.—Diagram of Shorts on Generator D.C.

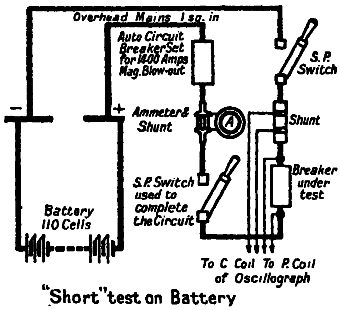


FIG. 20.—Diagram of Short Tests on Battery.

problem. As extra precautions are advised to prevent ignition of gases by the arc on rupture, the switch-case could be fitted either with finely divided "gauze," or a release valve, both of which act as cooling media, releasing the gases generated. These provisions, however, necessitate inspection, as dust may collect on the gauze, which must be kept clean to maintain efficiency.

Oil Switch D.C. Tests.—Figs. 18, 19 and 20 are diagrams of connexions showing the method of obtaining the following records. In the case of Fig. 18 the two generators were run up in parallel, supplying a current of about 920 amperes at 220 volts. The load consisted of an electrically-driven pump which delivered against a pressure equivalent to a head of 120 ft. The switch marked S.P. was kept closed while the load was adjusted; when this switch was opened

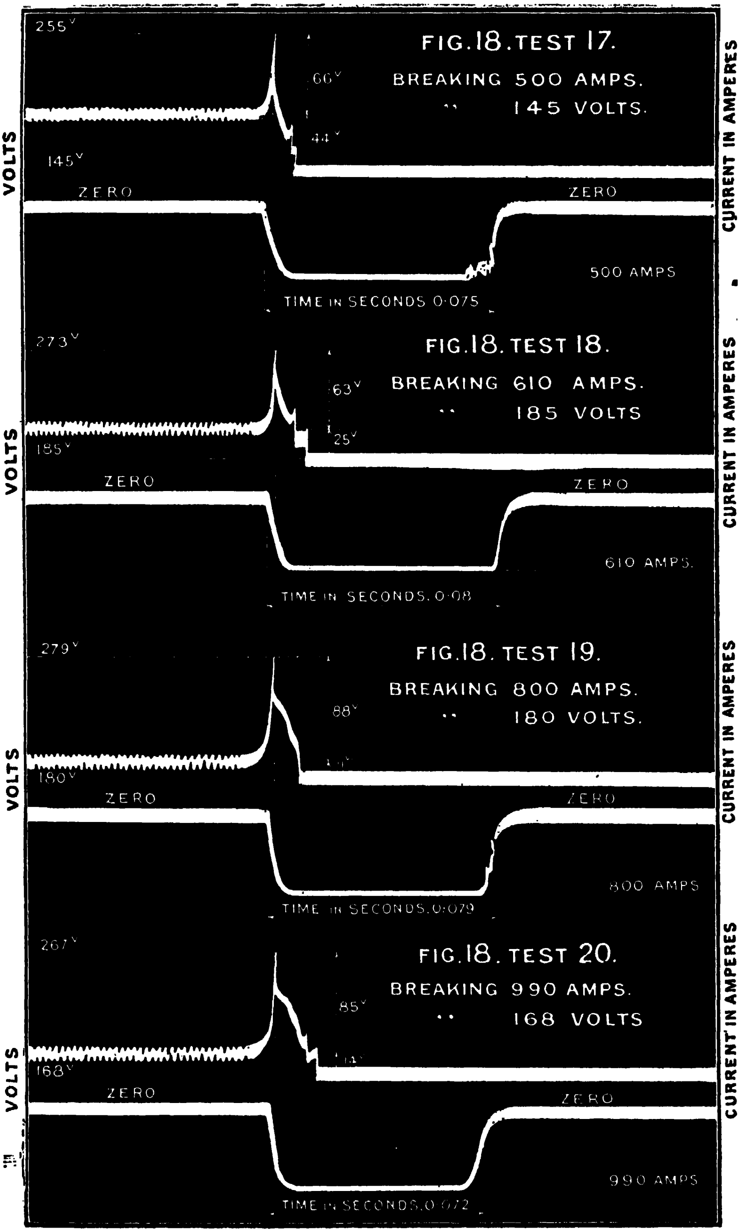


Fig. 18a.—Tests 17–18–19–20, Oscillograph Record of D.C. Oil Switch.

the apparatus under test automatically ruptured the circuit. Fig. 19 illustrates the method of making a short test on one

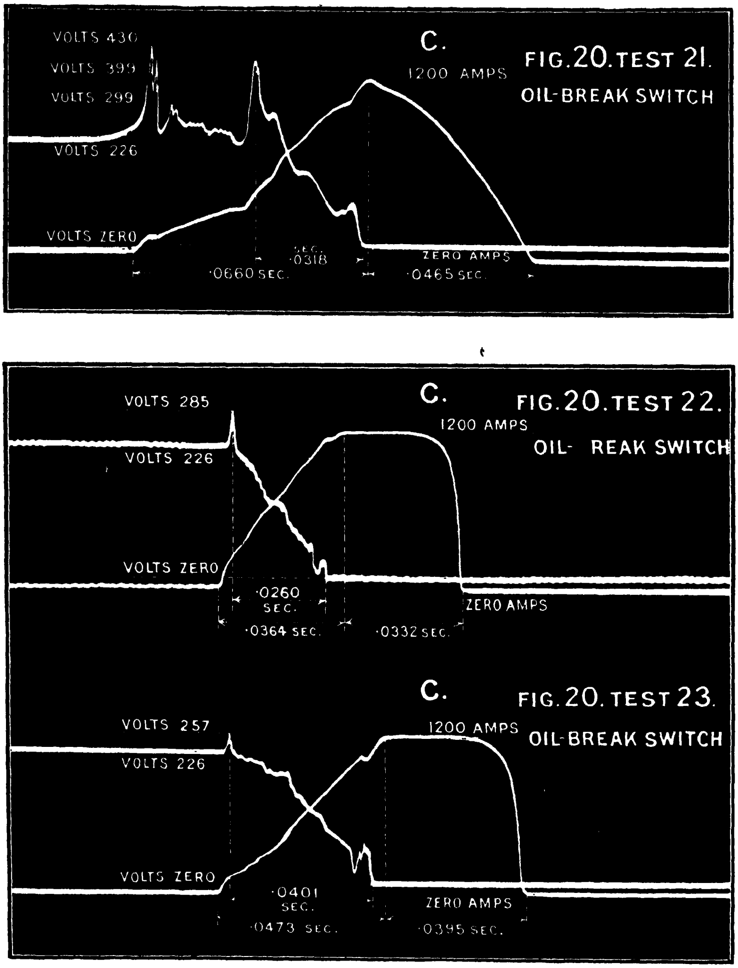


FIG. 20A.—Tests 21–22–23, Oscillograph Record of D.C. Oil Switches on Shorts.

of the generators, the capacity being 100 K.W. at 230 volts, inductive circuit.

Fig. 20. Diagram of connexions showing short test on the battery—the maximum rated discharge of which was 353 amperes.

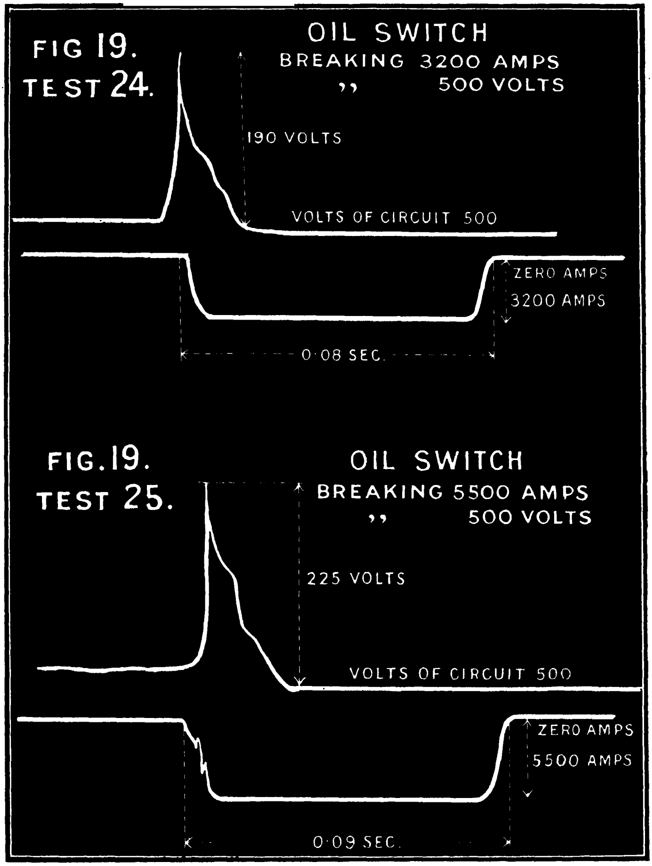


Fig. 20b.—Tests 24–25, Oscillograph Record of D.C. Oil Switches on Shorts.

Test 17 records a pressure of 110 volts above normal at 500 amperes, giving a total of 255 volts.

Test 18 records a pressure of 87 volts above normal at 610 amperes; total, 275 volts.

Test 19 records a rise of 88 volts above normal; total potential being 268 volts with 800 amperes flowing.

Test 20 records a pressure rise of 99 volts at 990 amperes; total pressure, 267 volts.

In all these tests the damping out of the arc by the oil can be seen and its rapid effect observed from the pointed character of the E.M.F. curve. The above tests will have some relation to further tests illustrated under D.C. switchgear, in this book, and the results in comparison with the

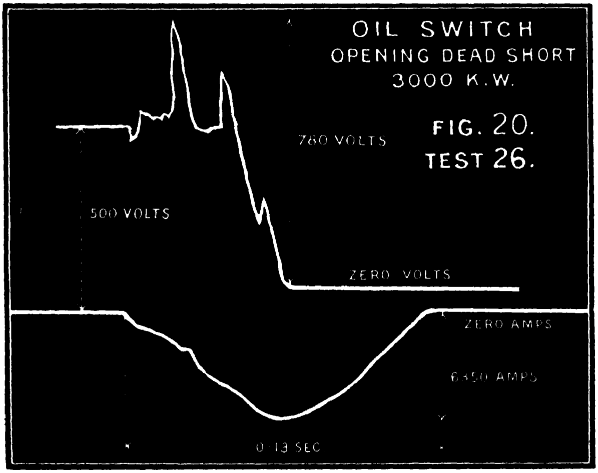


FIG. 20C.—Test 26, Oscillograph Record of D.C. Oil Switch on Shorts.

foregoing are shown in Fig. 21, where it will be noticed that the E.M.F. rise indicated at C (oil switch) is only slightly higher than that of the carbon break circuit-breaker and much less than that of other breakers. The time of opening the circuit averages 0·078 in seconds, or less than that occupied by the carbon break on busbar.

A series of tests were made to investigate the effects of opening inductive and non-inductive circuits. Tests 21, 22 and 23 illustrate the non-inductive effects obtained in connexion with diagram, Fig. 20. Tests 24, 25 and 26

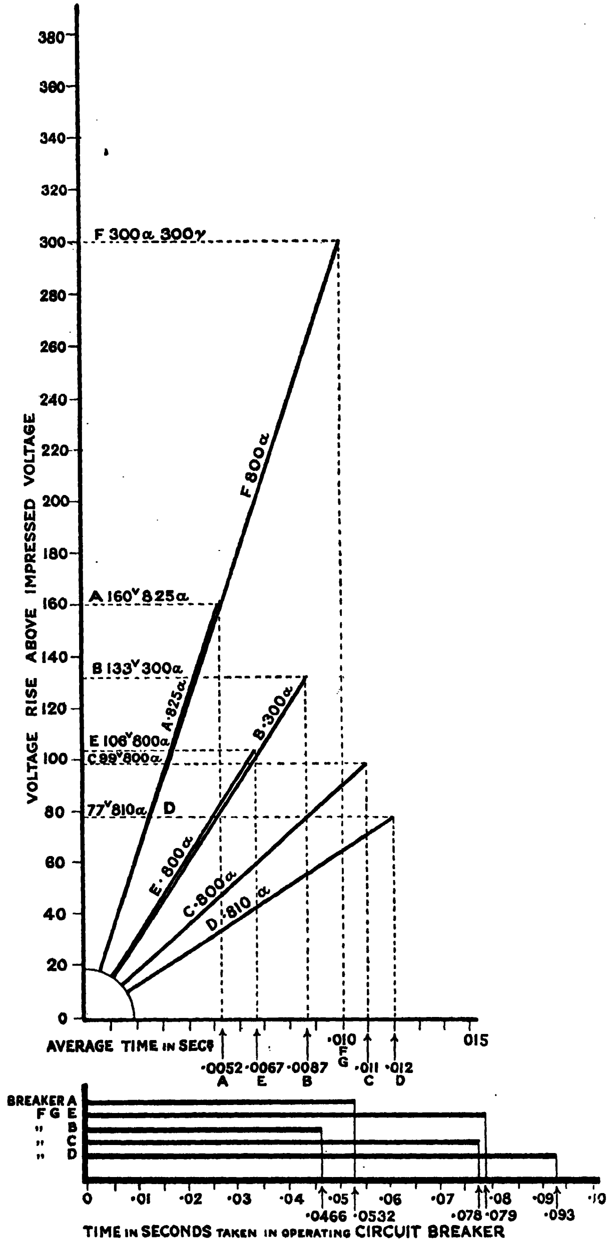


FIG. 21.—Comparative Results of Various D.C. Breakers.

illustrate the results of opening inductive shorts as in diagram, Fig. 19. The capacities at which these tests were made vary from 3,000 K.W. downward, representing the general requirements that this gear is called upon to fulfil.

Water Switch.—Test 27 (*see* below) records the result of opening a 500 ampere circuit at 180 volts, the "oil" dielectric being replaced by water. The current and voltage curves are very similar to those shown under oil switch ruptures. In some cases switches have been installed using oil and water for the arc damping medium. The water prevents vaporization of the oil, and, in addition, limits the

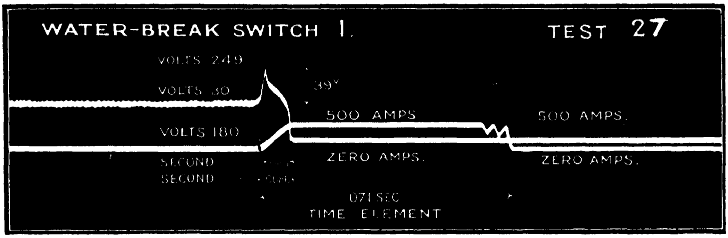


FIG. 21A.—Oscillograph Record of Water Break Switch.

induced voltage rise. Such provisions, however, appear quite unnecessary, as will be seen from the above test.

Oil Switches for Heavy Duties.—In central stations of large kilowatt capacity, and where space is not a limiting feature, it is often found desirable to instal electrically or pneumatically operated oil switches. Their adoption is principally governed by (1) installation in a separate room adjacent to that occupied by the generating sets, and (2) the necessity of rapid opening and closing of switches which require considerable mechanical effort. Obviously where the main switches are at a distance from the operating table the intervention of mechanical toggles and levers is by no means as efficient as the use of low tension currents operating a solenoid which closes the main contacts. The rapid

closing of large switches at the time of paralleling is vital to successful operating, and even if the mechanical gear of a switch is simple, the electrically operated switch acts more quickly and positively than any switch operated by hand. The time taken to close a 300 amp. 6,000 volt switch with an 8-in. break, after the synchronizing position has been reached, is 0·01 of a second. With this type of switch it is necessary that some arrangement be provided so that the switch cannot be closed inadvertently; the provision of a push-button switch on the operating table without "fool proof" interlocking gear would be foredoomed to failure. The switch must not be capable of being carried beyond the synchronizing position before synchronism has been obtained, and the completion of the circuit by energising of the solenoid operating the switch only take place after the switch has reached synchronizing position. This, of course, implies free handle mechanism.

Lightning Arresters.—The subject of protection from lightning is one of which at present comparatively little is known. Vicious surges which accompany accidental arcs again, are out of proportion to the arc formed, but their frequency and oscillation are governed by the nature of the installation and of the transmission. In the first place the destructive effects, due to lightning, cannot be measured, and their effects on the system are only known by calculation based on assumptions. Experience, however, has contributed towards protection against static charges and it is to these experiences we owe the development of the lightning arrester from the early horn pattern to that known as the aluminium type. The horn pattern of arrester, one of the first developments, is by no means superseded by other types; it is used almost as much as any other form, and its principles are embodied in almost every kind of H. T. switchgear, but the provision of more definite gear has developed designs that tend towards perfect protection. What is wanted is a protection that while serving its

purpose in the relief of static disturbances permits of the service being continued, and it is in this direction that the older forms of arresters fail. On a three-phase system, for example with neutral earthed the result of an accidental earth on one phase would be a short circuit of the Y leg of that phase. This would cause an interruption of service. Assuming the neutral to be insulated or earthed through a relatively high resistance a phase going to earth would not appreciably affect the voltage of the system, either Delta or Y, but such currents would be superimposed, in proportion to the electrostatic effect, that the system would become unbalanced. Since the charging current of the line is small in comparison with its power component, except on long transmissions, the potential due to charging is negligible. While there are many considerations in connexion with an earthed or unearthed neutral, it is generally understood that protection from surges and lightning on an unearthed system has a better chance than on a system permanently earthed. If an earth occurs on an unearthed three-phase system the potential of that phase above earth will be reduced to the effective potential across the arc. Thus the arc may be extinguished due to the falling potential across it. In connexion with a 60,000 volt scheme in Sweden, where, originally, the middle of the three-phase system was earthed, many interruptions were occasioned by external conditions which nearly all forms of lightning arresters failed to relieve. It was therefore decided to remove the earth, and entirely insulate the system, adding only lightning relays, and troubles are now of rare occurrence. This may have been due to the design of insulator.

Assuming normal conditions, with normal potential on the line, and without cutting off the supply, the arc vapours were cooler than the temperature of conduction. The relay referred to was connected in series with the secondaries of current transformers, and operated a single pole switch connected in each phase. These switches were arranged to

earth either phase during static disturbances, and would come into action when the potential was reduced by flash overs; a predetermined time was allowed to elapse before the relay opened the earth connexion. It is quite easy to discriminate between the phase which is earthed and those unaffected, since the potential of one is reduced while that of the others is increased. The relays superseded lightning arresters, and were fitted at various points along the line. From these results it would appear that the relay protection is the line along which developments should be directed in future. If further research were conducted in this direction the difficulty regarding external disturbances would be more satisfactorily met than by the further development of spark gaps. The relays installed on this transmission were extremely delicate. They required a good deal of attention, and their use on extra high potential systems is therefore impracticable. These relays depended upon electrostatic principles, but similar ones could be designed to operate electro-magnetically, the latter course rendering them of a still more delicate nature. It will be noticed that the author has hitherto urged simplicity and the exclusion of any form of relay, but special circumstances call for exceptional treatment. Every circuit containing capacity and inductance is subject to oscillatory phenomena. If capacity is predominant arc currents are of a vibratory character. This vibration sets up oscillatory impulses which may be of normal frequency or a multiple thereof. The wave length depends upon the absorption of energy. This oscillation may be dangerous when in resonance with, say, a transformer or the internal coils of a transformer. Resonance is not generally understood, as its appearance is, fortunately, not very frequent, but it implies "repeated oscillatory impulses." If an earth has a resistance in series equal to or smaller than the critical value as given by the equation

$$R = 2\sqrt{\frac{L}{C}}$$

each impulse will die out without oscillation. Hence discrimination must be exercised when earthing the neutral point of a generator through a resistance or choker. If resistance must be inserted it should be of the liquid type, as this has greater thermal capacity than metallic resistances, which have proved a source of trouble on this account. The variety of power transmissions involves corresponding differences in inductance and capacity, and resonance is very likely to appear if one of the phases is earthed through such a resistance. The increment of energy in the resonant surge is of minor dimensions relative to the power component. Resonance between coils of transformers is very rarely met with, as the natural frequency of a local surge is generally too high to resonate with the impressed voltage. An example has been recorded. A 356 K.W. transformer, 11,000 volts, has a natural frequency of 90,000 cycles per second. An arc lighting transformer has a natural frequency of 3,000 cycles per second. This shows how impossible it becomes to bring such high values within the range of the generator frequency. Electrostatic induction is of uniform character; its intensity, however, varies according to the formation and the distance of the cloud burst. The electrostatic induction depends upon the position of the aerial line relative to the cloud; it is magnetically repelled to earth, via the transmission, where it is met by the self-induction of the system. Thus the potential builds itself up across the insulators. Rapid electro-static induction, however, involves heavy current rises at the instant of collision. Hypothetically one could compare it with the collision of water in a confined area, the water pressure forming a bulb in the centre. In a similar manner heavy currents are induced by the opposing influences of electrostatic induction. These currents find their way to earth via the lightning arrester, or by the operation of a relay providing the necessary path. Static charges are not entirely confined to the point of maximum disturbance, but extend,

possibly, over many miles of transmission line, and if not arrested destroy all line insulators in their path. If arrested the action must be instantaneous, considering that the charge travels along the line at the rate of 200,000 miles per second. It is reasonable to suppose this rate of travel to have been the cause of some of the gap arresters failing, since it takes time to produce the vapour which bridges the contacts. Dynamic investigations provide us with the data required for further designs. Assume a transmission at 100,000 volts. If a charge of lightning of 0·0011 coulombs travelled at its natural speed of 200,000 miles per second, or allowing for the opposing force of self induction, 150,000 miles per second, the resultant current wave would be 1,700 amperes, and to keep the potential undisturbed at the source of supply would require the discharge to be dissipated at the same rate. If the charge oscillates at 10,000 cycles per second it would resolve into a current of 9 amperes. Owing to the different cloud strata and the variable sphere of electrostatic induction, influenced by one or more charges the effects of lightning cannot be constant, and, naturally, an inconstant condition cannot be met by a constant, so that, whatever provision is made, its range of influence must be wide and flexible. Hence on some extra high potential transmissions rather than run risks attending external charges, the line is practically screened by wires in direct connexion with the earth. The chief difficulty, however, is electro-magnetic induction. Corona effects follow in the wake of lightning discharges. The brush discharge only slightly exceeds that of the normal potential; in fact, aerial wires have been increased in diameter in order that the brush discharge shall be above the impressed pressure. There is, therefore, on disturbance a superimposed potential causing loss of energy in the form of chemical action on the atmosphere, and its discharge is persistent along the line until it is trapped and sent to earth.

Current and Potential Transformers.—In the measurement of energy on high potential circuits the indicating instruments are connected to the secondary windings of transformers. The phase angle and the characteristics of such transformers are illustrated by diagrams showing the Y connexion delta, open delta, the Z connexion and the V connexion. These connexions illustrate how far their particular angles comply with the accurate setting of the relay and indicating meter, and particular attention is directed to such connexions when used for the measurement of watts or energy. Transformers may be either "air cooled" or "oil cooled," according to the voltage of the system to which they are applied. It is generally the practice here to use oil-cooled transformers on voltages exceeding 3,000. This, however, is not absolute, as other features may not be consistent.

The volt-ampere output of transformers must exceed the power required for the operation of the instrument by a considerable margin. Ring transformers should not be applied when accuracy is demanded on the secondary side, but may be quite suitable for operating the trip coil of a switch. Where especial accuracy is demanded over a wide range of current and voltage, or at low power factors, the relation between phase angle and ratio becomes a proposition. So far as ratio is concerned potential transformers do not constitute such a problem as current transformers, seeing that the primary voltage is fairly constant and small variations can be easily compensated by the phase angle. Current transformers have a variable condition to meet. Generally speaking, when current transformer ratios are the same value from full secondary load to small secondary load the meter accuracy is unaffected, since this ratio, whatever its value, is taken care of by calibration of the meter. If, however, the ratio bends upwards at low loads, and vice versa, the meter accuracy is affected unless some compensation is provided. In interconnecting secondary loads for current

transformers the load is connected in Y formation. The difference between this load and the ordinary load connected Y to power transformers is that the power circuit operates with practically constant voltage, while the current and the impedance of the device connected change together; on the Y supplied by current transformers the impedance of the devices remains constant, the current and voltage changing together.

Using the standard method of calculation we get as connected in Fig. 38—

$$1 - Z_A = r_A - jx_A$$
$$2 - Z_B = r_B - jx_B$$
$$3 - Z_C = r_C - jx_C$$

The currents flowing are 1, 2, 3. Thus, if ϕ represents length of lag by which current 2 lags behind current 1 and B the ratio of r.m.s. currents 1 and 2,

$$2^c = Bc^1 (\cos \phi + j \sin \phi)$$

as the connexion is as Fig. 38 we get—

$$3^c = - C^1 - C^2 = - C^1 - SC^1 (\cos \phi + j \sin \phi)$$

As regards voltages we get—

$$e^1 = C^1 (r_A - jx_A)$$
$$e^2 = C^2 (r_B - jx_B) = Sc^1 (\cos \phi + j \sin \phi) (r_B - jx_B)$$
$$e^3 = C^3 (r_C - jx_C) = (- C^1 - Sc^1) (\cos \phi + j \sin \phi) (r_E - jx_C) = - C^1 (C + S) (\cos \phi + j \sin \phi) (r_C - jx_C).$$

The open and closed delta voltages and the reversed V connexion as seen in Figs. 33, 34, 35, 36, etc., can be subtracted in the same manner.

The volt-ampere output is the product of the secondary current with its secondary voltage. The power factor is given at a definite current and voltage, the cosines of the angle are the power factors of an assumed load.

If E represents pressure, C current, and taking 5 as the volt-amperes of the transformer we get—

$$EC \times \frac{25}{C^2}$$

If two transformers are used on a three-phase circuit the combined voltages give the figure at which they operate.

If three transformers are used and connected in Y they divide the delta voltage according to Y conditions, the phase position being a function of the load and the nature of the transformer.

With the ordinary straight connexion for transformers the load under balanced conditions on all three transformers is 1·73 times that on one of the three transformers, the power factor of the secondary output is 30°, one lagging, the other leading. In the case of two transformers the volt-amperes of each transformer equal the sum of the volt-amperes in the two lines directly connected to the two secondaries and three times those in the secondary line without transformer, the whole divided by two.

In the case of three straight-connected transformers each transformer load equals the sum of the volt-amperes of the three secondary loads divided by three. Trip coils that demand 50 volt-amperes should be operated by 60 to 70 V.A. transformers. Synchronizing potential transformers for synchronoscope should be 60 V.A. capacity and transformers that operate indicating instruments in series with trip coils should be calculated on a basis of the maximum V.A. to operate trips with at least 10 V.A. as margin over and above the V.A. consumed by the meters. A properly built transformer will take care of ageing and leakage, and latterly troubles due to this cause are very infrequent. The inaccuracies of wattmeters operated with and without transformers are shown in this book; such errors, however, are small and need not affect their ratings.

CHAPTER III

Reverse Protection—Reverse Current—Phase Relationship—Wattmeter Relays—Inductive Balancing—Wattless Component—Characteristics of Generators—Induced Voltages—Calculations—Excitation—Energy of Limitations—Transformer Protection—Examples of Connexions—Z Connexion—Three-phase Protection—Method of Transformer Connexions—Feeder Protection—Time Limit Appliances—Balance Protection—Ring Main Feeder Protection—Ring Transformer Protection—Synchronizing—Paralleling—Choker Synchronizing—Disposition of Currents in Paralleled Alternators.

Instruments for Protecting Alternating Current Circuits.—These are classified as follows :—

(1) Reverse ; (2) overload ; (3) inductive balancing.

The first serve to open a circuit when there is a reversal of energy or displacement between the current and E.M.F.

(2) The function of the second is to open circuit when current flows in excess of a predetermined setting.

(3) The balancing of current or E.M.F. when the system or different parts of the system show signs of stress due to abnormal conditions.

Reverse Protection.—The control of A.C. energy returning to its source is an exceedingly difficult problem. Many designs are claimed to discriminate and open circuit on reversal, which, judging from practical results, are generally ineffective. The term " Reversal of Energy " is often misquoted ; " Reverse Current," for example, which is quite a misconception ; it should be defined as implying that condition of an A.C. circuit when the current at every instant is

flowing in the opposite direction to that of its source, or 180° out of phase. When a current lags or leads by 90° it is neither a forward nor reverse current, as during half of its cycle it is flowing in the same direction as the E.M.F. and for the remaining half in the opposite direction. Diagrammatically, in Fig. 22, we have flowing into the circuit two currents superimposed upon one another, viz., B and C, the latter being either a reverse or forward current. B is the current we should consider; it is at every instant flowing in the opposite direction to the E.M.F. and is the power component of the current D. If D lags behind the E.M.F. by an angle less than 90° (see D^1), no reversal takes place; but there is a current of amplitude E, acting in the same direction as the E.M.F. Relays which operate upon reversal of energy (as measured by a wattmeter), whether of the rotary or plunger type, have two windings, one energising in proportion to the line voltage, the other in circuit with the secondary of a current transformer. In the case of the plunger type of relay these coils normally oppose each other, but on reversal their effects are cumulative. The difficulties met with in their design are that they fail to operate when the "Potential" falls below a predetermined value, but are entirely dependant upon "Power Factor." The latter introduces problems that cannot be solved by one instrument. Circulating and wattless currents between sets constitute formidable difficulties. For this reason modern switchgear designers are very reluctant in advocating reverse protection, and in many cases, supply

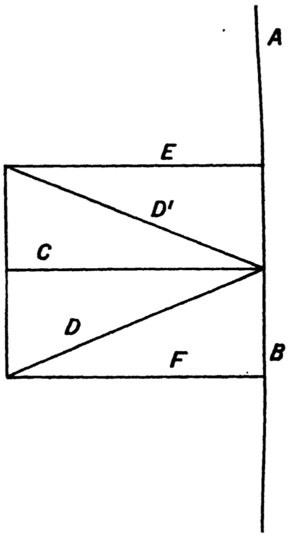


FIG. 22.—Reverse Relay Diagram.

authorities, owing to the inconvenience experienced, have cut their relays out of action. On a large supply undertaking the reverse power relays opened up a 5,000 K.W. turbo-generator which was overloaded at the time, when paralleling a 1,000 K.W. reciprocating set, thus leaving the latter set to deal with the load which at that time was 7,200 K.W. This set responded by opening out its end windings and stripping the machine. The total damage was computed at £3,300.

Characteristics of Generators.—In high speed turbo generator sets there is a difficulty in obtaining uniformity of characteristics. When such machines are switched into parallel with other sets the trouble is accentuated. The introduction of variable frequencies in the E.M.F. wave still further emphasizes the difficulty. When machines are paralleled their induced E.M.F.'s are opposed and if the capacities are similar the wattless components will be equal. If the phase angle of the induced E.M.F. of one set is in advance of the other, the induced voltage would be unaffected. The geometrical difference between the two E.M.F.'s sets up cross currents between machines; these cross currents lag behind the induced E.M.F., the angular difference being proportional to the phases of the E.M.F.'s and determined by the inductive reactance, which is in turn proportional to the resistance and reactance. If this wattless component is in phase on one set and not on the other it becomes a plus quantity in the case of the former and minus in that of the latter. Thus we get a transfer of load with an affected "Power factor."

The general formulae for the induced E.M.F.'s of generators is—

$$E\,1 = 4\ k\ w\ k\ j\ f\ n\ \phi\ 10^8$$

The equation for the induced E.M.F. for transformers is—

$$E\ 1 = 4{\cdot}44\ f\ n\ \phi\ 10^8$$

Wattless Component.—Fig. 23 illustrates the effect of field adjustment of two machines of equal load at unity power factor with the circuit composed principally of inductance or reactance. By increasing the induced E.M.F. machine volts 1 are in phase with machine volts 2. As machines have equal capacity there is an actual line current C22 due to combination with its wattless component 4 which lags 82° from the machine volts 2. Thus we arrive

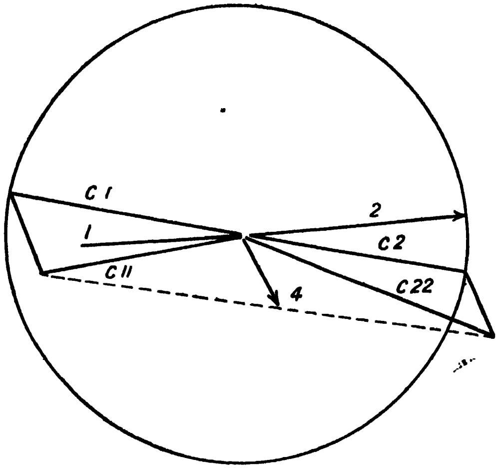


FIG. 23.—Diagram of Wattless Component.

at the C11 value of the curve in the other machine showing the transfer of the wattless component. The above is based on the assumption that each set has equal synchronous reactance and that the generated voltages have no relative phase displacement. As stated before, the wattless component is contingent upon the characteristics of the machines about to be paralleled. The equation of copper losses in both machines is given as follows—

$$\frac{\mathrm{E}w^{o1}}{\mathrm{E}w^{o2}} = -\frac{\mathrm{R\,E}\,w^{2}}{\mathrm{V} + \mathrm{R\,E}\,w^{1}}$$

$\mathrm{E}w^1$ = Represents the energy and wattless component of

the interchange current. (R) resistance of armature, (V) terminal voltage. The minus sign signifies that if the load is inductive, the power supplied by the alternator increases as the excitation is diminished. As an actual example, with full load current the drop of the alternator at the time of parallel connexion, is, say, 15% of the terminal voltage.

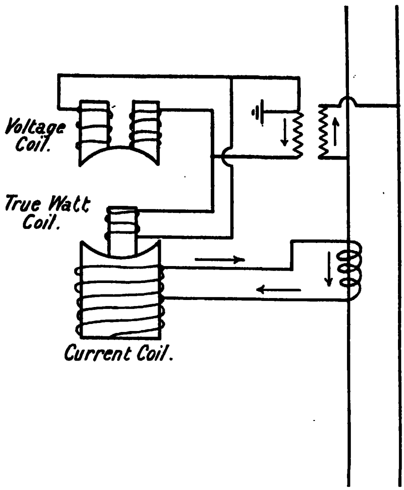


FIG. 24.—Reverse Relay Connexions.

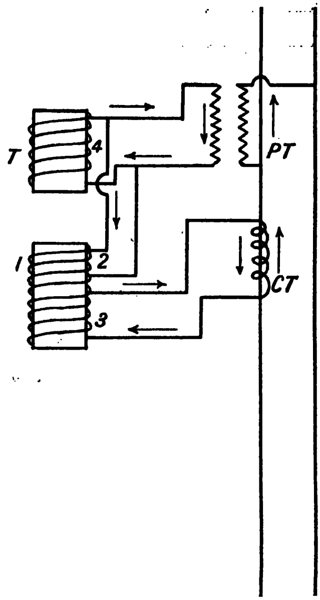


FIG. 25.—Reverse Relay Connexions.

Assuming the load is inductive, and the full load current of one alternator at 0·707 P.F. and the interchange of current produced by change of excitation be equal to full load current we get—

$$\frac{Ew^{o1}}{Ew^{o2}} = \frac{0{\cdot}707 \times (2 \times 0{\cdot}15)}{V + 0{\cdot}707 \times (2 \times 0{\cdot}15)} = 0{\cdot}17$$

Thus the alternator with the smaller excitation will take

58 per cent. of the total load and the one with higher excitation will take 42 per cent. of the total load.

Figs. 24 and 25 show an arrangement of relays operating on the "true watt" principle. On core 1 there is a shunt winding 2 and a series winding 3, on T there is the shunt winding 4 connected in parallel with shunt winding 2. The windings (2) and (3) oppose each other in the forward direction, hence a greater current will be caused to flow through (3) for a predetermined torque. On reversal of

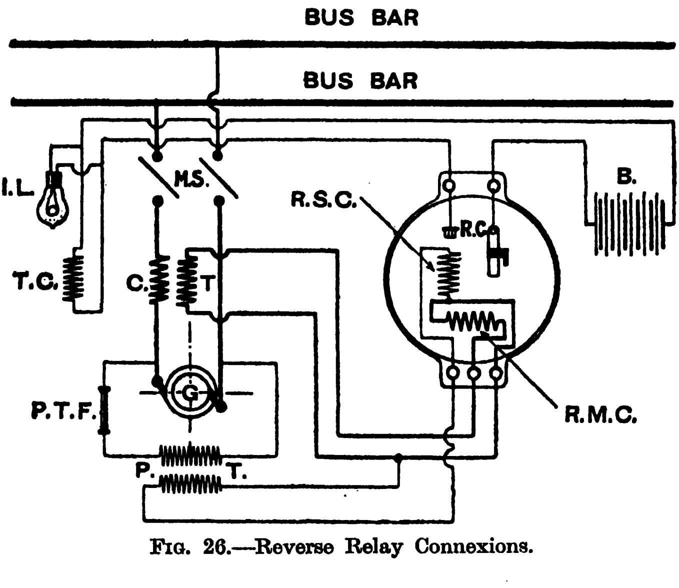


FIG. 26.—Reverse Relay Connexions.

energy these two coils assist, hence less current is required to operate the trip mechanism.

Fig. 26 illustrates a form of reverse current relay, the coils of which operate a rotary disc and open the circuit on a reversal of energy; they are limited in scope as above referred to.

Balance Protection.—Fig. 27 is a diagrammatic arrangement of a form of balance relay for the protection of generators. A potential supply from the busbars or transformers

is connected to the centre of the secondary winding X Y of the series transformer. As the coil is wound entirely in one direction, and as there are an equal number of turns on either side of the point of potential connexion, the current from the bars will divide equally between the two halves, and these currents will have an equal and opposite magnetizing effect upon the core of the transformer. The outer connexions of the secondary winding referred to are connected to two solenoids A and B, and so long as the current in these solenoids is equal the magnetic pull on the swinging armature is equal and opposite. The current flowing from the generator into the bus-bars will induce a secondary current in the local circuit X A B Y, in the directions indicated by the full arrows, and will so far disturb the inductive balance as to cause a greater current to flow through the branch X A than through the branch Y B, with the result that the pull due to gravity, tending to hold the relay in the open position shown, will be supplemented by a magnetic pull approximately proportional to the current. On reversal, the current flows through the series winding relatively to the direction of current due to the potential supply. The series current will now induce a secondary current in the opposite direction to the arrows.

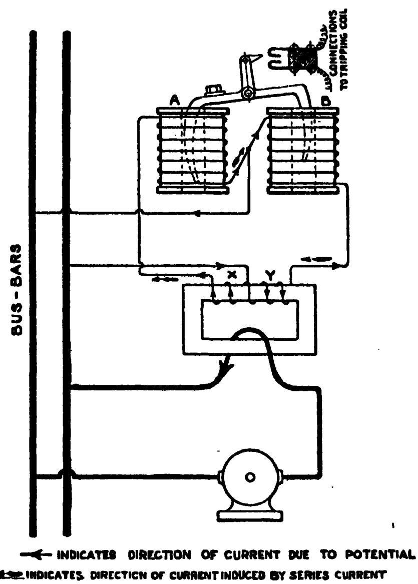


Fig. 27.—Reverse Relay Connexions with Inductive Balance.

Protection of Transformers.—Fig. 28 illustrates a form of protection for the above. The currents in the secondaries tend to oppose, and under normal conditions the E.M.F.'s

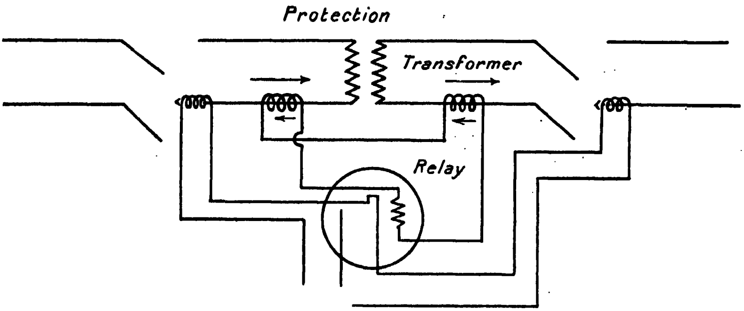


FIG. 28.—Method of Balance Protection.

are equal. If a short or partial short occurs on the transformers the ratio is altered, hence one of the transformers will overpower the other and open circuit. A similar form of connexion is shown in—

Fig. 29, in which case the series transformers are not

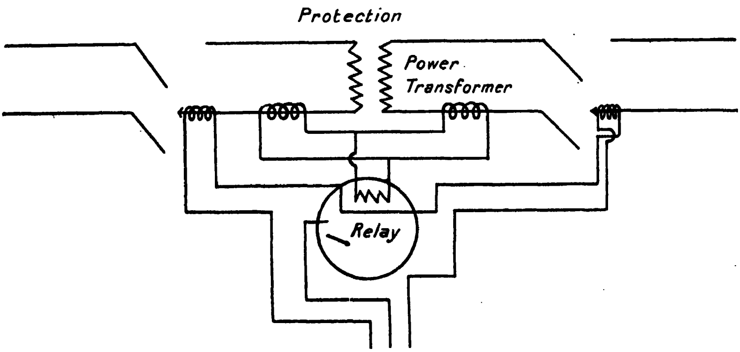


FIG. 29.—Method of Balance Protection.

opposing each other and the E.M.F.'s of the open circuit series transformers need not be equal. If the currents on either side of the power transformer are unequal, the secondaries of

the series transformers will be likewise, since current will be larger on one transformer than the other, which current will operate the trip coil. In the case of Fig. 28 there are no copper losses because no current is flowing, and the relay would act more positively in the case of a short circuit, as the current through one of the transformers must pass through the relay coil. Against this, the iron loss would be greater than in the case of Fig. 29, as iron is saturated when current flows only through the primary, and the E.M.F. in the secondaries may assume a high proportion, because of a virtually open circuit. The

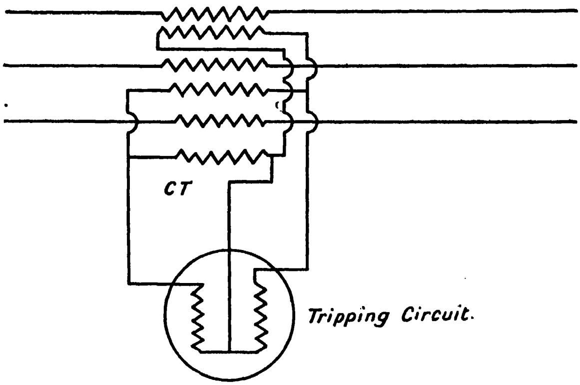


FIG. 30.—Diagram of Z Connexion.

transformers must be identical in construction. If the iron ages more in one than in the other the E.M.F.'s on open circuit may, assuming a definite proportion, operate the relay. Combinations of these schemes may be applied in many ways to suit definite requirements.

Overload Protection Secondaries connected in Z.—Two transformers are not sufficient for the protection of a three-phase circuit, as the third phase is left unprotected from short circuits to ground. Three transformers connected in Z are similar to a delta connexion with the common transformer reversed as indicated in Fig. 30. There is an advan-

tage in using this connexion over that of the straight delta, as in the latter each element of the relay receives current which is the resultant of the current in the two transformers to which it is directly connected. Thus if each transformer has 5 amperes flowing, the resultant will be $\sqrt{3}$ times $= 8{\cdot}66$ amperes. An overload in one phase only will therefore affect the relay less than an overload on two or more phases. If, however, the series transformer which is common to the two elements of the relay is reversed at its terminals, the Z connexion is obtained. The 5-ampere currents in the series transformers will now combine to form a 5-ampere current to the relay coils instead of an 8·66 ampere current. It is desired that the relay shall act when the current in any of the individual phases reaches a certain value independent of the current in the other phases. Obviously the relay should not act when the current in each of the phases is materially lower than the tripping values, even though the vector sum of two of the phases may be greater. The Z connexion secures this condition as the effect of an overload in one phase only is nearly the same as an overload on all phases. Thus the relay action is determined by the maximum current in any one phase, rather than the sum of the currents in the different phases. Transformers connected in Z do not, however, give the proper phase relation in the resultant circuits for the operation of wattmeters or similar apparatus into which

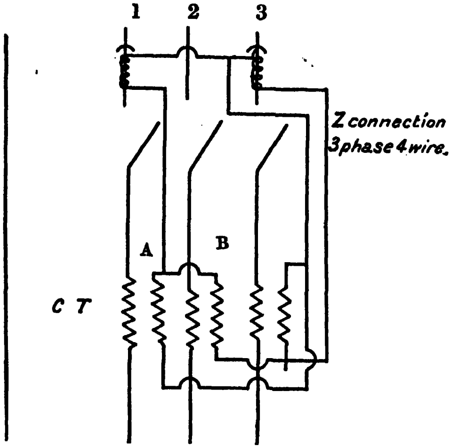


FIG. 31.—Diagram of Three-phase Four-wire Connexion.

the phase relationship of current and voltage enters. With a given line current at which tripping is desired the relay current per element is determined by the ratio of the series transformers.

Three-Phase Protection Four-Wire.—Fig. 31 shows the connexion for a three-phase four-wire circuit. (A) protects phase 1 and 2 and (B) protects phase 2 and 3. By examination of these diagrams it will be seen that it protects against shorts or grounds on either phase.

Single - Trip Protection.—It is often found necessary for the protection of three-phase systems (insulated) to use only one trip coil. Fig. 32 shows a diagram of such an arrangement. The secondaries of the two transformers are cross connected.

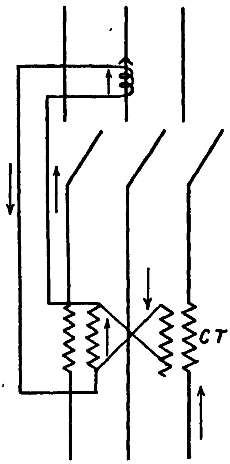


FIG. 32.—Overload Protection, one Trip Coil.

Methods of Transformer Connexions.—The vectorial relation of secondary current to primary of transformers is not generally known. There are many ways of coupling up these secondaries to suit various applications. A few of the most common examples are as follows—

Fig. 33 shows the reversed V connexion. The straight lines represent the magnitude and phase relation of the E.M.F. to neutral. The zig-zag line represents the phase relation in each transformer. The E.M.F.'s in Figs. 34 and 36 between secondary lines are proportional and in phase with the primary E.M.F. The most common methods of connexion are the "delta" and the Y. The phase angle of the delta connexion is 120° and conforms with the voltage between lines (Fig. 37). The Y connexion differs from the above inasmuch as each transformer has a separate lead, which is connected to a corresponding terminal.

Common points may be added to suit other requirements with additional phase splitting connexions (see Fig. 38).

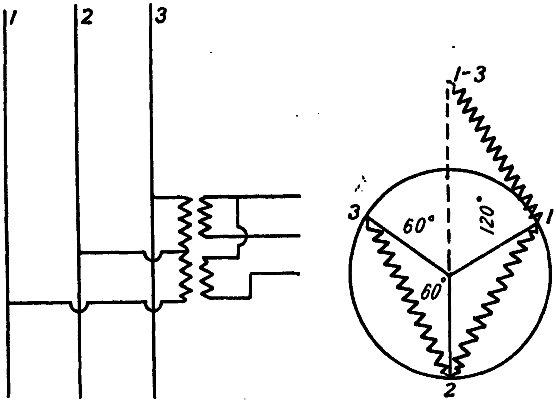


FIG. 33.—Reversed V Connexion.

The open delta is often used with its common lead connected to opposite terminals. The current in the common lines is in phase with the voltage between common lines (see Fig. 39). A form of reversed V connexion is shown in Fig.

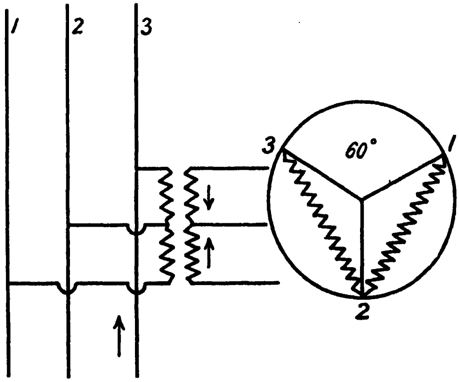


FIG. 34.—Open Delta Connexion.

40, one lead being common to the two transformers connected through the same common terminal. The phase difference of currents is 120°, with each phase current differing from the

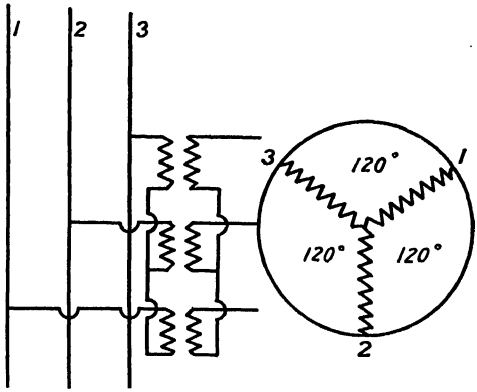


FIG. 35.—Diagram of Y Connexion.

two line voltage terminals by 30°. The overloading of transformers by connecting in common relays, wattmeters, trip coils, etc., is not good practice, on account of large impedances which introduce excessive transformer errors. The

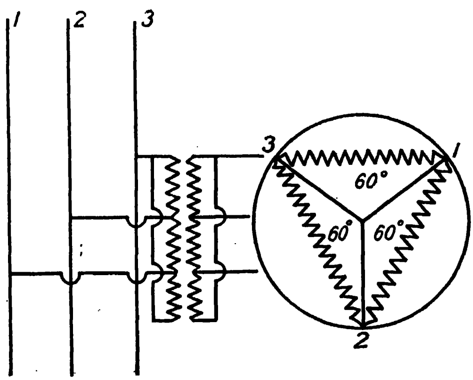


FIG. 36.—Diagram of Closed Delta Connexion.

breakdown of one link in the chain puts out of commission all other apparatus connected with it.

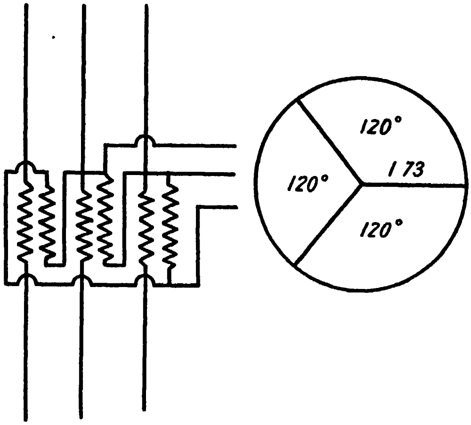


FIG. 37.—Diagram of Delta Connexion.

Feeder Protection.—The methods of feeder protection are usually confined to overload tripping devices, which may have a time limit or act instantaneously. The difficulty

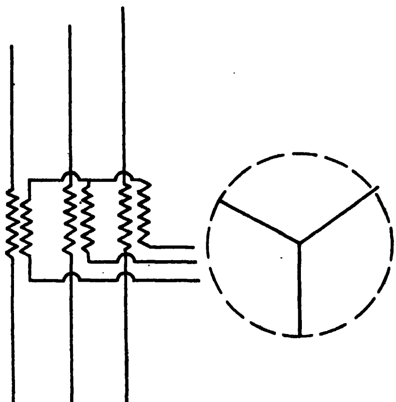


FIG. 38.—Diagram of Y Connexion Current Transformer.

about time limits is that their selectiveness is not to be depended upon.

Time Limit Appliances.—Fig. 41 shows the curve of a rotary time limit relay. Its action is inverse, and it will be

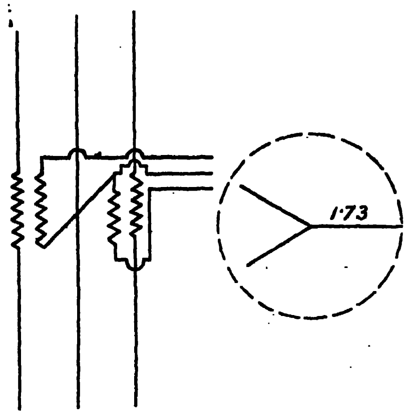


FIG. 39.—Diagram of Open Delta Connexion Current Transformer.

noticed the short time the relay takes in opening a short circuit; this is as it should be, but in the protection of a feeder distribution, when the circuit must be relieved at

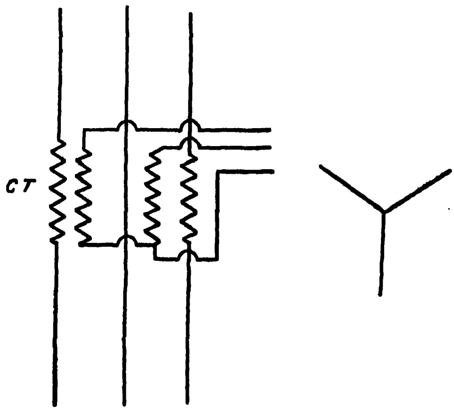


FIG. 40.—Diagram of Reversed V Connexion Current Transformer.

this point without disconnecting other healthy feeders, the margin for discrimination on a short condition is not

sufficient for this purpose, hence other devices are necessary.

Figs. 42 and 43 illustrate arrangements of time limit and instantaneous relay. Often in order to get time limit actions a form of dash pot is fitted at the extreme end of the switch solenoids. These are sometimes of oil, glycerine, or air. The latter act on the principle of a tyre valve, but are not

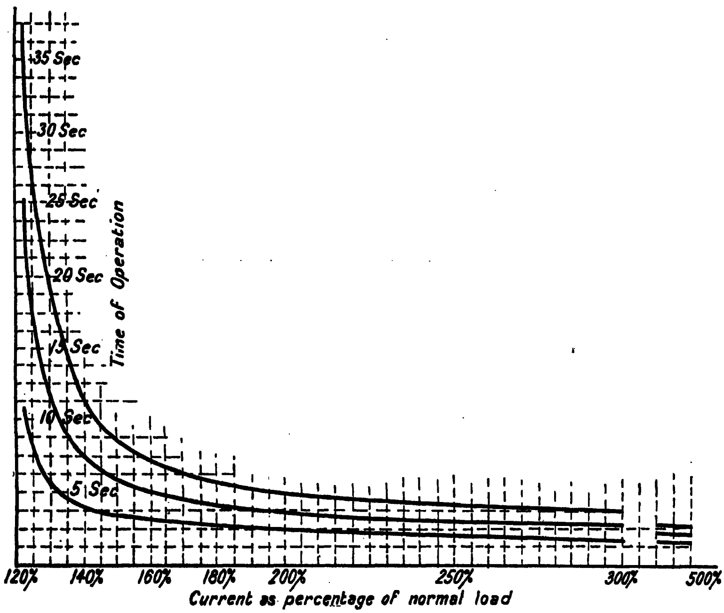


FIG. 41.—Overload Time Curve.

so popular as those of the oil type. Regulation is not so convenient, and the hammer blow to release the toggle is not so good. The oil or glycerine type after the time limit has expired releases the plunger and strikes the toggle in a positive manner. One form of time limit consists in placing a fuse in the secondary circuit of the current transformer, in parallel with the trip coil (see Fig. 44). Current normally passes through the fuse owing to the

high reactance of the trip coil; when fuse blows the current passes round the trip coil and operates the switch.

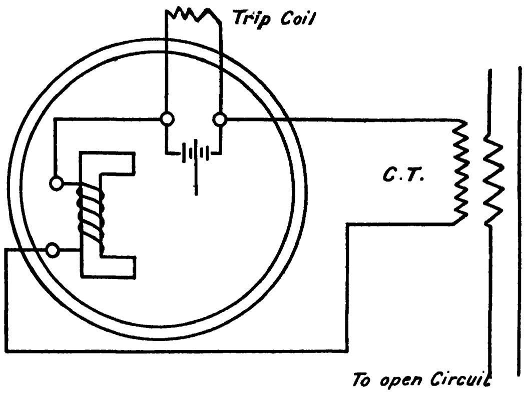


FIG. 42.—Diagram of Instantaneous Relay.

The fuse has practically no time limit on short conditions, and it suffers from the disability of being unable to change

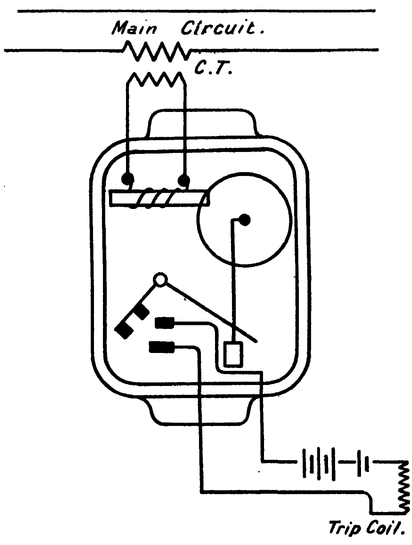


FIG. 43.—Diagram of Time Limit Relay.

the time independently of the current values. For feeders of the radial type, plain overload coils are very satisfactory. In the case of duplicate feeders through a sub-station it is often found that some other method of protection is necessary.

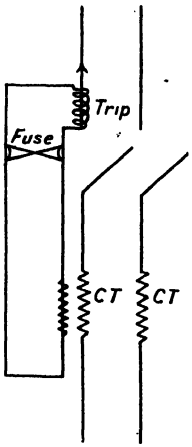


FIG. 44.—Diagram of Time Limit Fuse Strip.

Assuming that two feeders converge to a sub-station, and that one of the feeders went to ground, current could flow both ways into the earth from the source of supply or via the sub-station bars. To limit this return current into the earth possibly reverse energy relays might be installed, but as their energizing coils are limited by the fall of potential to within, say, 15 or 20 per cent. of the normal, and as a short may reduce the potential to zero, these relays would not be of much service.

Balance Protection.—The application of a choke coil with an E.M.F. balance meets the problem in a more positive manner (see Fig. 45). At the distributing centre the respective feeders are connected through a few turns of wire wound on a common iron core, the supply being taken off the centre point of the winding. Obviously under normal conditions the load will be divided equally between the two feeders, and consequently the iron will be magnetized in one direction by the current in the one feeder and in the opposite direction by the current in the other. The result is that a balance is established and consequently no back E.M.F. induced in the coil, the C^2R drop being very small. Should a short occur at A the automatic breakers C will open. The current will then tend to return to the short circuit from the other feeder via the winding D. The whole of the current will now magnetize the core in the one direction and its induction will be such that the induced E.M.F. is approximately equal and opposite to the applied E.M.F.; the amount of current,

therefore, that can flow into the short is cut down to about ¼ normal current. The healthy feeder at B will not be opened as the current will be insufficient for this purpose. The induced potential across the coil D is equal to the applied potential. The induced potential across half the coil will be equal to half the applied E.M.F., and as long as the fault is left connected to the system 50 per cent. of normal voltage remains in the circuit. This system may be extended in many forms, Fig. 45 serving to demonstrate the principle and its possibilities.

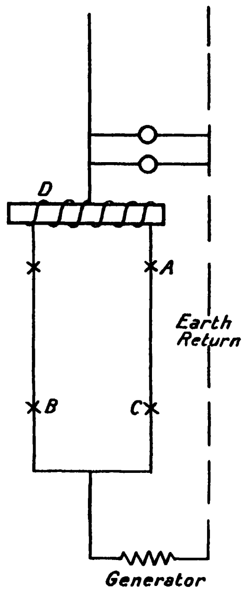


FIG. 45.—Diagram of Feeder Protection.

Ring Main Feeder Protection.—Power station supply companies often loop up feeders into a form of ring and again connect this ring to a radial feeder. Should a short occur on a section of the ring this should be isolated without disconnecting other portions of the ring. It is quite possible to arrange each substation board through which the ring passes, so that in the event of a fault this section could be automatically isolated and the supply continued by the service of the radial feeder, or the other portion of the ring that remains healthy. That is, the opening of a fault will close the service for distribution automatically in the other healthy feeders. When provision is not made for this a balance feeder protection is sometimes installed. There are a great many objections to this form of isolation, first, expense, and second, delicacy. The introduction of pilots, or the provision of a pilot circuit, is naturally expensive and its adaptation is very difficult on stations where the distribution is solid. The extreme sensitiveness of the relay

is the more important, as a healthy feeder may be cut off during supply. In cases where the out of balance on the primary side is set low, the relays are operative on pilot capacity currents, and inductance is another feature which requires consideration.

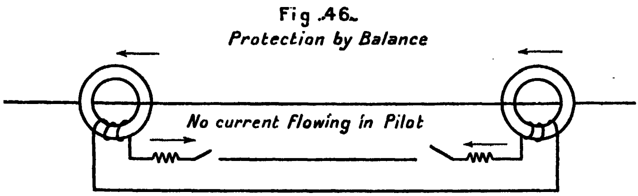


FIG. 46.—Diagram of Protection by Balance.

Fig. 46 illustrates this system of electrical balance, and in the case shown, as no fault lasts, no current is flowing through the pilots. In the case of Fig. 47 a fault is shown; the direction of the primary current is thus changed to the direction of the fault. The currents flow through the pilot in a similar manner, operating the relays. In the former case currents in the pilots are equalized. Fig. 48 illustrates the cutting off of an unhealthy feeder section of a ring and Fig. 49 shows the adaptability of this protection for power trans-

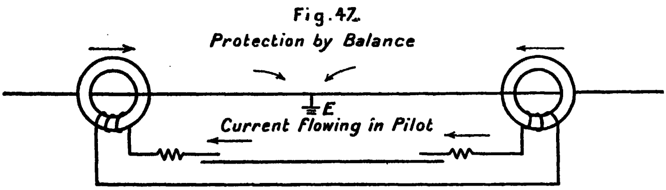


FIG. 47.—Diagram of Protection by Balance.

formers. The theory underlying the principle of this protection is that a balance is created under normal conditions between the power which is flowing at the points of entry and exit from the feeder. In the case of Fig. 47 assuming there is a fault at E an excess of current will pass through trans-

former 1 into the fault E, and excess of current will pass through transformer 2 into this assumed fault. As the current is not balanced by that through the series transformer (1), the E.M.F. of transformer 2 exceeds that of trans-

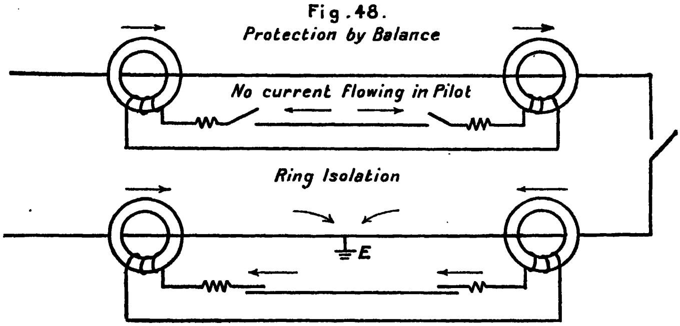


FIG. 48.—Diagram of Protection by Balance.

former 1, thereby destroying the equilibrium of the pilot circuit, in consequence of which current flows through the relays. In the case of transformer protection a time limit is necessary to prevent the relays opening when switching on. The momentary rises due to switching unbalance the system.

Ring Transformer Protection.—Consider a generating station from which a number of H.T. cables diverge as radial

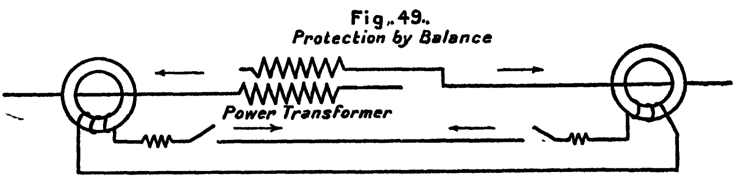


FIG. 49.—Diagram of Protection by Balance.

distribution. If there be no earthing on any particular feeder or on the network connected thereto the sum total of the current in the three cores must be zero at *every instant,* and this is true independently of whether the load be balanced or not. If then the feeder cable be surrounded by

the magnetic circuit of a ring transformer there will be no total magnetization in it. Now although we assume that no point of the system is connected to earth, there will be a certain capacity current from each pole of the system to earth via the cable di-electric, and the total capacity current flowing to earth at any instant must equal the capacity current flowing from earth to one pole via the di-electric. If there was an earth on this pole this part of the system would be at ground potential. The capacity current to earth from the other phases must find its return path through the section at earth potential, and consequently the whole capacity current must pass from earth via the fault. As an illustration, if we had twenty healthy feeders and one faulty

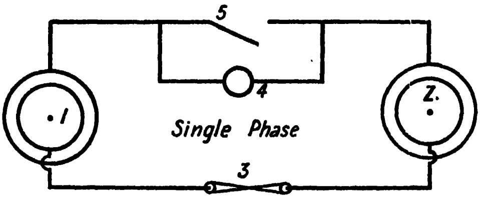


FIG. 50.—Diagrams showing Synchronizing by Lamps S.P.

one with an earth on one core, the capacity current flowing to earth from the twenty healthy feeders would be restricted in its return path to the faulty one. Assume this capacity current is 30 amperes, then the induction in the magnetic circuit round the faulty cable would be due to 30 ampere turns, and will be quite independent of the load on the feeder, while the induction of the transformer cores of the healthy feeders will be on an average due to 1·5 ampere turns, the total capacity assumed to be equally divided between the twenty healthy feeders. A ring transformer round a cable can be made to operate a relay with 30 ampere turns which in turn can open a switch or give alarms.

Synchronizing.—The paralleling of generators involves the use of gear indicating their position, such as lamps,

voltmeters, or synchronizers. Fig. 50 is a diagram illustrating the paralleling of two S.P. alternators. Across the switch and in parallel with it is a glow lamp, which should be capable of standing double the voltage of either machine. When the switch is opened the lamp is in series with the machines, the circuit being a closed one. If these machines were for continuous currents either their voltages would be added or they would be in opposition; in the latter case the voltage would be zero. In the case of single-phase machines accord-

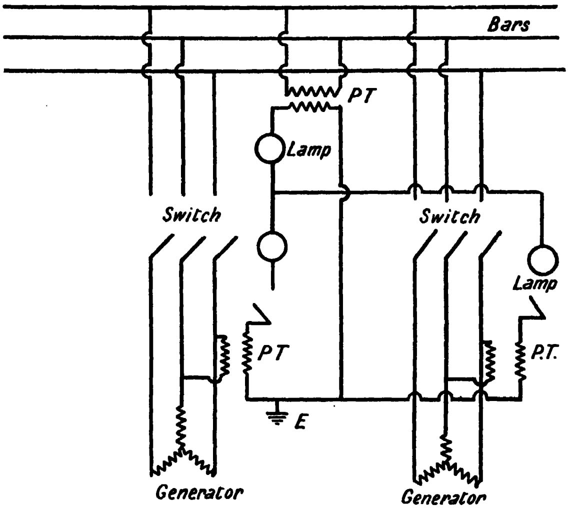


FIG. 51.—Diagrams showing Synchronizing by Lamps Three-phase.

ing to their phase displacement their values may be doubled or at zero. If one machine was slower than the other the lamp would indicate this by glowing at one time and not at another. If the phases of the machines were separated by half a period the lamps would be at maximum intensity. It is more convenient to synchronize with lamps alight than dark, as fluctuations and phase displacements are more easily recognized. The lamp in this case instead of being connected in parallel with the switch is connected across the

main circuit. Instruments such as voltmeters can be used in place of lamps, to show the phase relationship which will be indicated by the needles.

Fig. 51 is the diagram of an arrangement for paralleling three-phase machines with lamps.

The lamps indicate phase position by the pulsations of the lamps. On power supply systems the usual method is to employ a synchronoscope with two lamps in series. Such connexions are more complicated and costly. Fig. 52

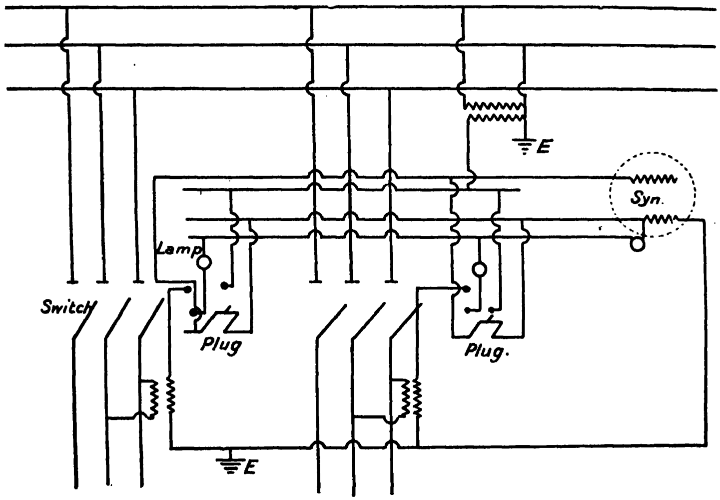


FIG. 52.—Diagrams showing Synchronizing by Lamps and Synchronoscope.

shows the connexions using synchronoscope and lamps, with no interlocking, the latter, of course, being necessary when operating solenoid switches. For paralleling generators it is necessary that all receptacles and plugs are interchangeable; the centres must be such that the pilot connexions cannot be made in the wrong direction. The earthing of one side is also a necessity, so that in the case of a partial ground, excessive potentials do not present themselves. The rotary synchronoscope is built on the principle

of a small induction motor, the magnetic field of which will revolve at the same speed if the frequency is consistent, the rotor remaining in the position coincident to the two main fields paralleled. There is a high non-inductive resistance in series with one phase and a high reactance in the other. If transformers are used they should be not less than 40 V.A. capacity. A very popular method of synchronizing is that known as the three-lamp method. An advanced form of paralleling gear is sometimes used in which lamps are arranged in an equilateral triangle, so that in proportion to the E.M.F.

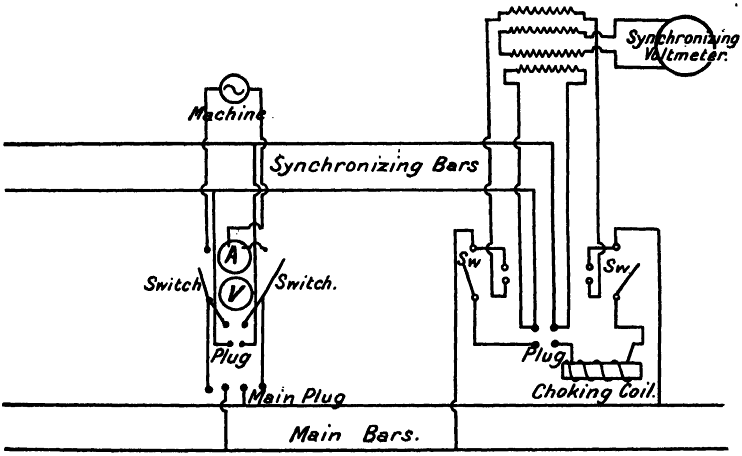


FIG. 53.—Choker Form of Synchronizing.

of phase displacement, the lamps indicate the speed by the travelling round of the light on the main glass and the triangle. The subject of paralleling is dealt with under reverse current relays, hence it will not be necessary to repeat the discussion, but to refer back to this chapter for further information.

Choker Synchronizer.—A very safe form of synchronizing gear is illustrated in diagram Fig. 53. The great advantage with this equipment is that machines can be switched on load right out of phase and pulled into phase by the

choker. Thus bad shots and other attendant difficulties are eliminated. This form of synchronizing is superior to others now in use in this particular respect, that at any time a machine can be placed in circuit whether in phase or not in phase, and without the use of the field regulators will take its portion of the load in phase with the external prime movers by the action of the choker. To power station engineers this is a boon, especially when their equipment consists of machines having totally different characteristics. The initial expense of providing for such equipment is greater

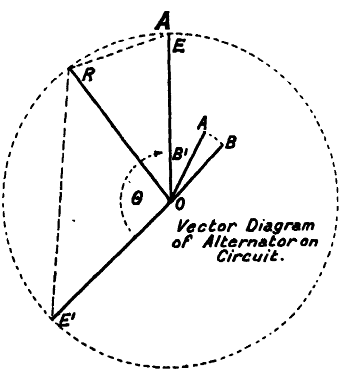


FIG. 54A.—Vector Diagram of Alternators.

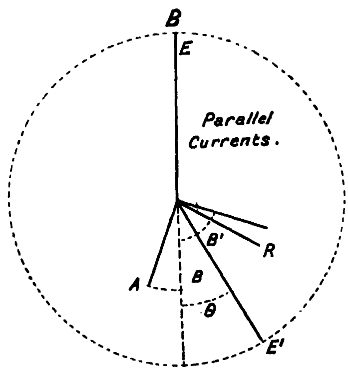


FIG. 54B.—Vector Diagram of Alternators in Parallel.

than with other forms of paralleling gear, since it necessitates the use of extra high tension bars and connexions. This, however, is practically an unimportant item in comparison with the advantages of the gear. Many station generators have been shut down and generators burnt out in paralleling, and it is conceded that such failures would not have occurred had this gear been in use. As the machines are being brought into phase the iron core is drawn out of the choker and eventually short circuited. The regulation of alternators by the manipulation of their excitation, for paralleling, should be adopted with the greatest discrimination as pointed out under

reverse relays, as the inductive application of the rheostat has been responsible for many failures.

Disposition of Currents in Paralleling Alternators.—Fig. 54 (A,B,) illustrates the notation and disposition of the circuit under paralleling operations. In Fig. 54 A (E) denotes the potential difference, (E^1) the open circuit E.M.F. to a given excitation, (A) the armature current per phase. OE represents the P.D. and OE^1 the E.M.F. induced in armature winding. The vector resultant OR of these two gives the E.M.F. available for overcoming the armature impedance. As (A) representing the armature current per phase lags behind OR by an angle whose tangent represents

Armature Reactance.—From the reading of this diagram $OB^1 = OA$ on OE^1 then $E \times OB^1 = EA \cos. 10$ E the electric power of the circuit.

$E^1 \times B = E^1$ A $\cos. \phi$. The conversion of energy. Assuming a definite self-inductance, B diagram is similar to diagram A = OE = P.D., OE^1 = E.M.F., OR impedance drop in armature, OA current which lags behind OR by an angle $\tan.^1 \frac{LP}{R}$. The electric power developed is given by $E^1 \times OB^1$. The power to the busbars is $E \times OB$. The increase of ϕ is an increase of power. The decrease may set up phase swinging, the results of which are pointed out under reverse relays. The use of the excitation therefore modifies each condition relative to these curves.

CHAPTER IV

MEASUREMENT OF OUTPUT—EXAMPLES—WATTMETER ERRORS—INTEGRATING WATTMETERS—GENERAL PRINCIPLES—VARIOUS METER CONNEXIONS—AMMETERS—VOLTMETERS—INDUCTION METERS—GENERAL PRINCIPLES—CALCULATION—FREQUENCY METERS—EFFECTS OF INDUCTANCE AND CAPACITY.

Measurement of Output.—So many errors have been made in the connecting up of wattmeters that it was considered of some value if a series of diagrams were given representing various methods and standard practice. For reference Fig. 55 contains six diagrams for service on single phase systems with and without transformers, Fig. 56 the connections used for two-phase three-wire circuits with and without transformers, Fig. 57 gives the connexions of meters used on two-phase four-wire circuits, with and without transformers; Fig. 58 connexions of three-phase meters balanced and unbalanced three-wire with and without transformers; Fig. 59 shows the connexion of meters on three-phase four-wire circuits balanced and unbalanced. Fig. 60 diagram of connexion of three-phase three-wire unbalanced load wattmeter. Fig. 61 of a meter with the neutral point not available. Fig. 62 of a similar instrument with the neutral point available, and Fig. 63 diagram of three-phase four-wire unbalanced wattmeter.

Wattmeters Errors.—Figs. 64, 65 and 66 illustrate the errors due to varying power factors, voltage, and frequency, and are recorded tests taken on a standard meter. In connexion with the use of wattmeters, current transformers when used in conjunction should be as accurate as possible

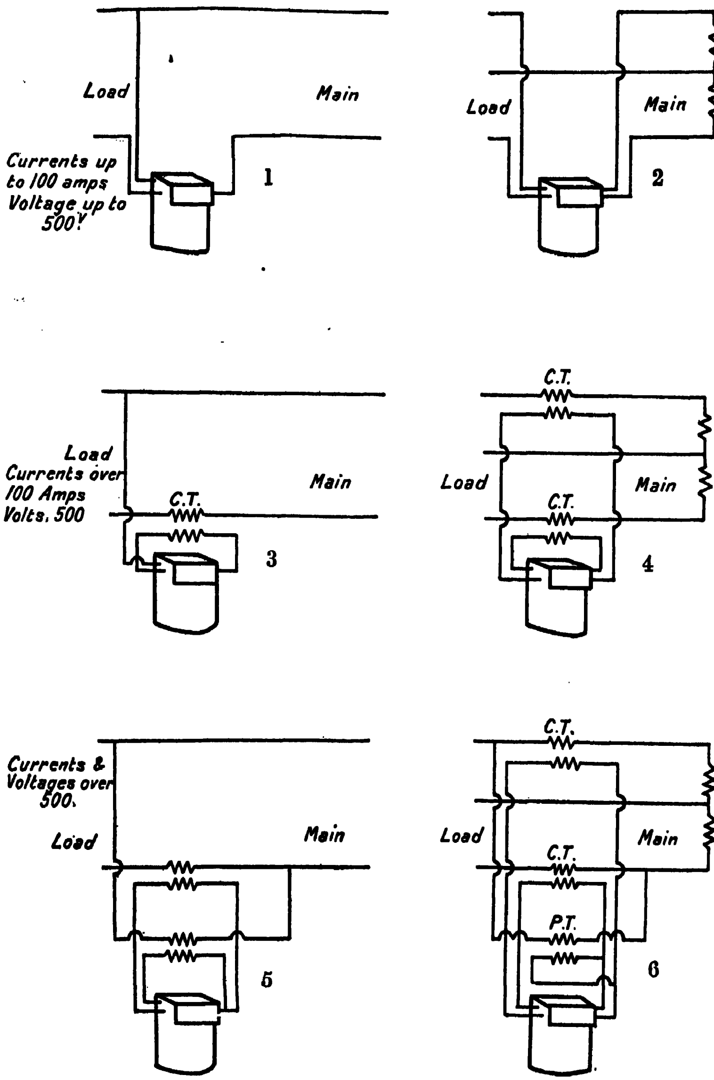


FIG. 55.—1. Diagram of S.P. 2 Wire Wattmeters. 2. Diagram of S.P. 3 Wire Wattmeters. 3. Diagram of S.P. 3 Wire Wattmeters with Transformers. 4. Diagram of S.P. 3 Wire Wattmeters with Transformers. 5. Diagram of S.P. 3 Wire Wattmeters with Transformers. 6. Diagram of S.P. 3 Wire Wattmeters with Transformers.

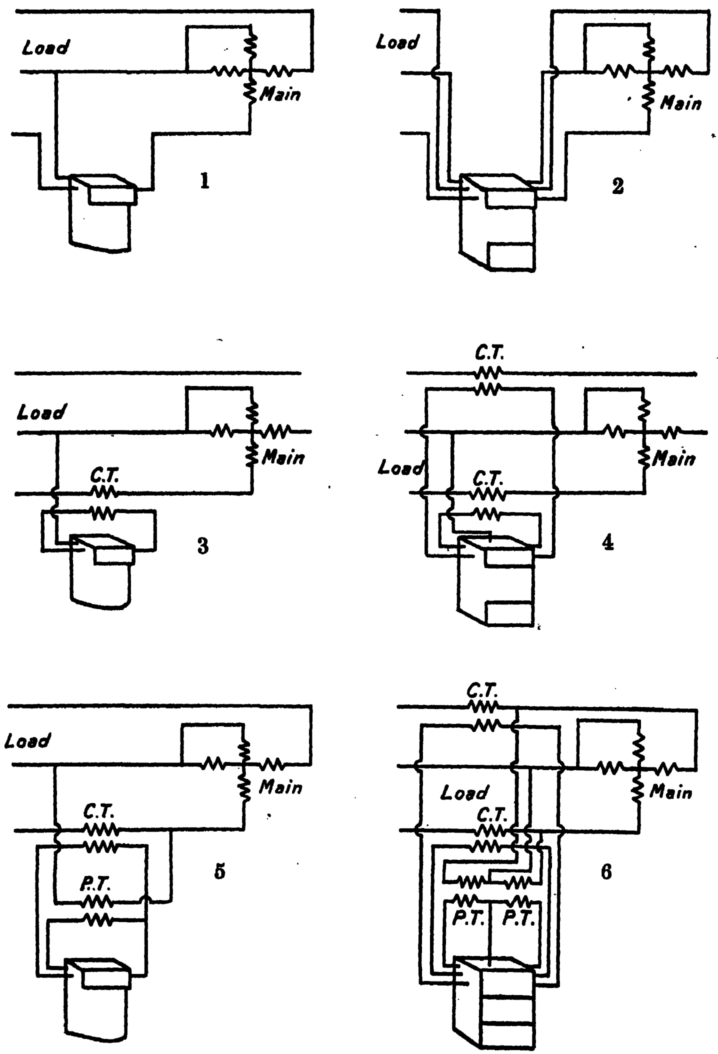


FIG. 56.—1. Diagram of 2 Phase 3 Wire Wattmeters Balanced. 2. Diagram of 2 Phase 3 Wire Wattmeters Unbalanced. 3. Diagram of 2 Phase 3 Wire Wattmeter Transformers. 4. Diagram of 2 Phase 3 Wire Wattmeter Transformers. 5. Diagram of 2 Phase 3 Wire Wattmeter Transformers. 6. Diagram of 2 Phase 3 Wire Wattmeter Transformers.

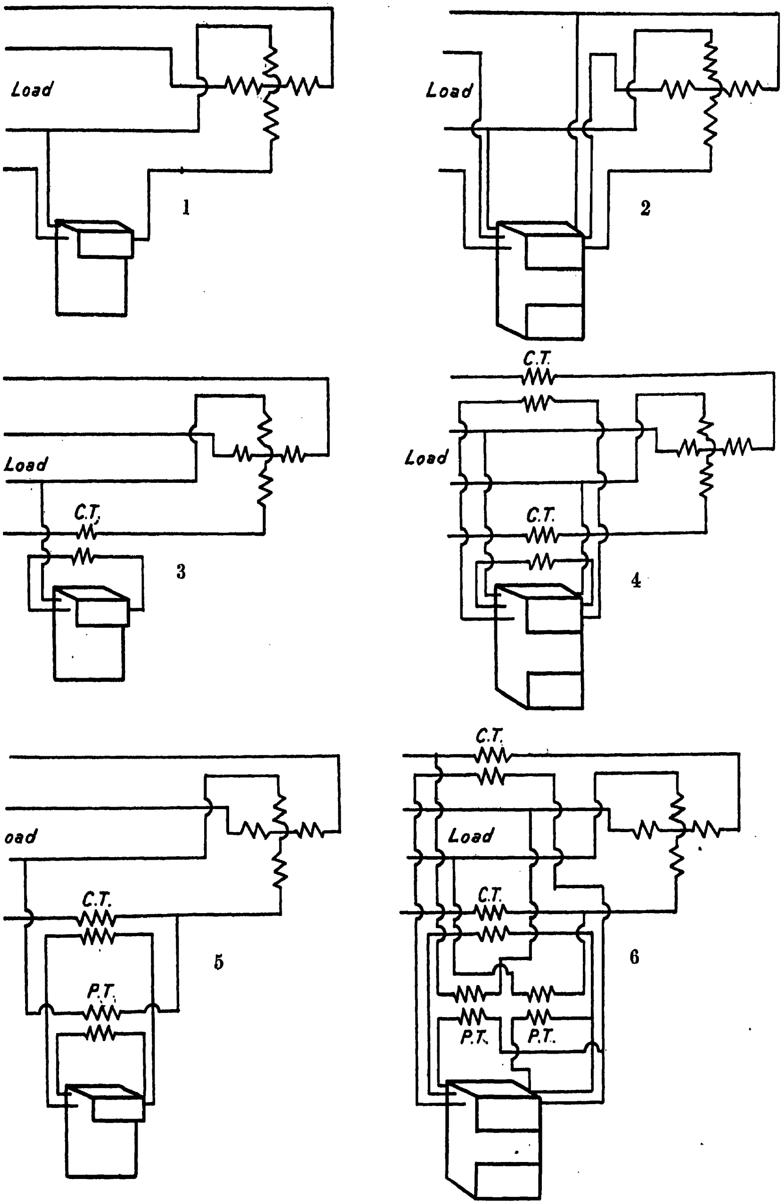


FIG. 57.—1. Diagram of 2 Phase 4 Wire Wattmeter Balanced. 2. Diagram of 2 Phase 4 Wire Wattmeter Unbalanced. 3. Diagram of 2 Phase 4 Wire Wattmeter Transformer. 4. Diagram of 2 Phase 4 Wire Wattmeter Transformer. 5. Diagram of 2 Phase 4 Wire Wattmeter Transformor. 6. Diagram of 2 Phase 4 Wire Wattmeter Transformer.

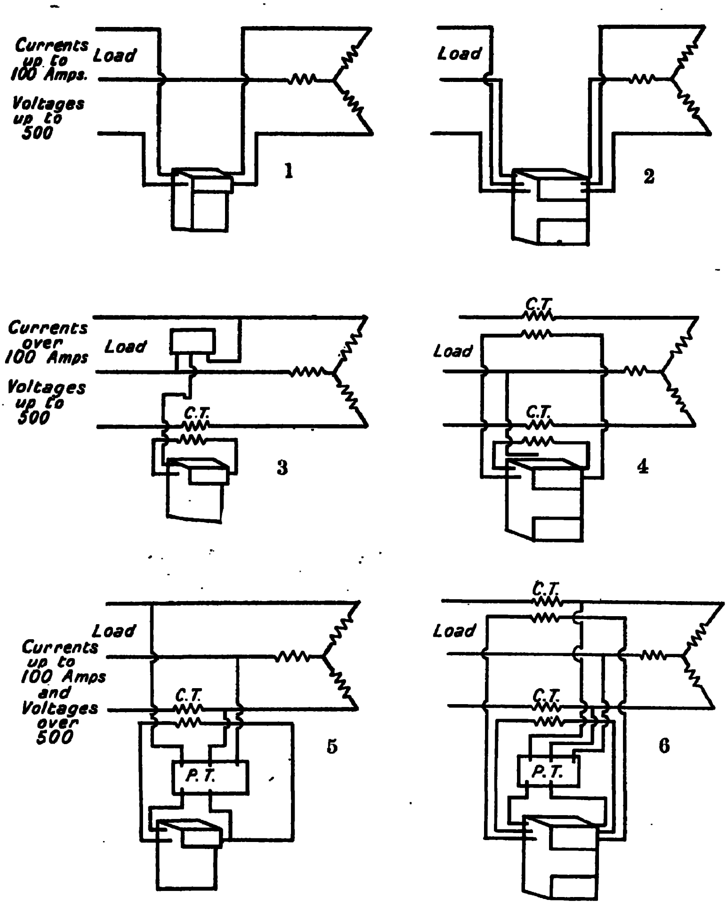


FIG. 58.—1. Diagram of 3 Phase 3 Wire Wattmeters Balanced. 2. Diagram of 3 Phase 3 Wire Wattmeters Unbalanced. 3. Diagram of 3 Phase 3 Wire Wattmeter Transformers. 4. Diagram of 3 Phase 3 Wire Wattmeter Transformers. 5. Diagram of 3 Phase 3 Wire Wattmeter Transformers. 6. Diagram of 3 Phase 3 Wire Wattmeter Transformers.

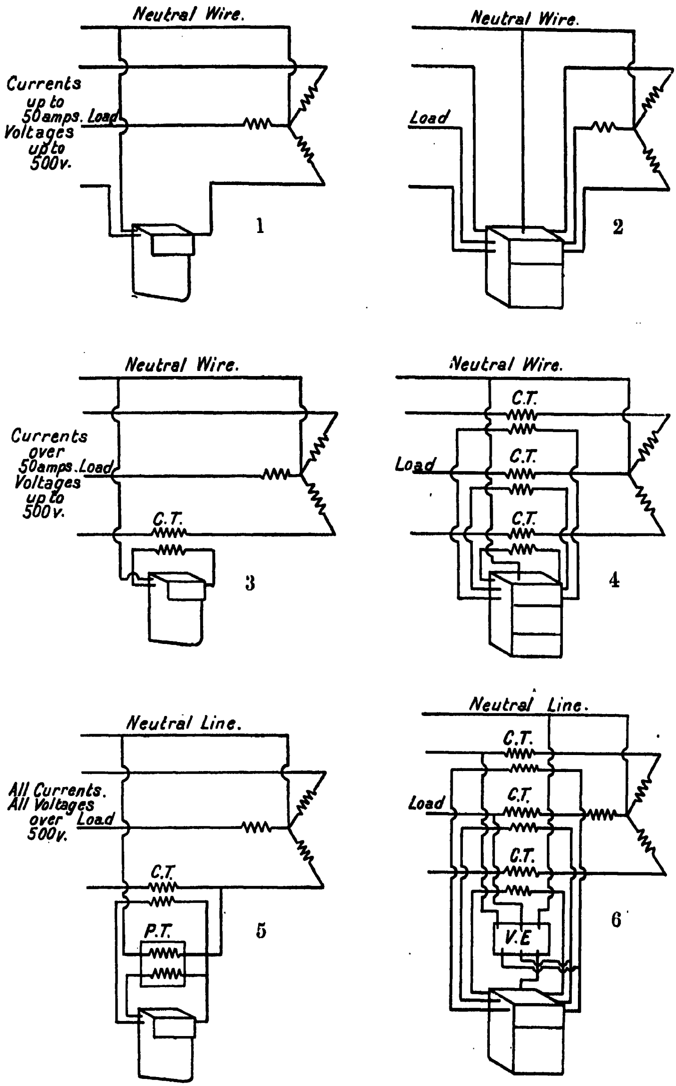


FIG. 59.—1. Diagram of 3 Phase 4 Wire Wattmeters Balanced. 2. Diagram of 3 Phase 4 Wire Wattmeters Unbalanced. 3. Diagram of 3 Phase 4 Wire Wattmeter Transformers. 4. Diagram of 3 Phase 4 Wire Wattmeter Transformers. 5. Diagram of 3 Phase 4 Wire Wattmeter Transformers. 6. Diagram of 3 Phase 4 Wire Wattmeter Transformers.

at all loads. Small transformers are not found accurate at low loads and power factors. If the instrument connected in series with the secondary of a transformer is working at a quarter of its full load capacity a cheap transformer may be found accurate enough. Fig. 67 shows the percentage variation from full load to $\frac{1}{10}$ load, the variation being about 7 per cent. Fig. 68 shows the accuracy of a wattmeter between full and $\frac{1}{10}$ load by connecting this meter in series with

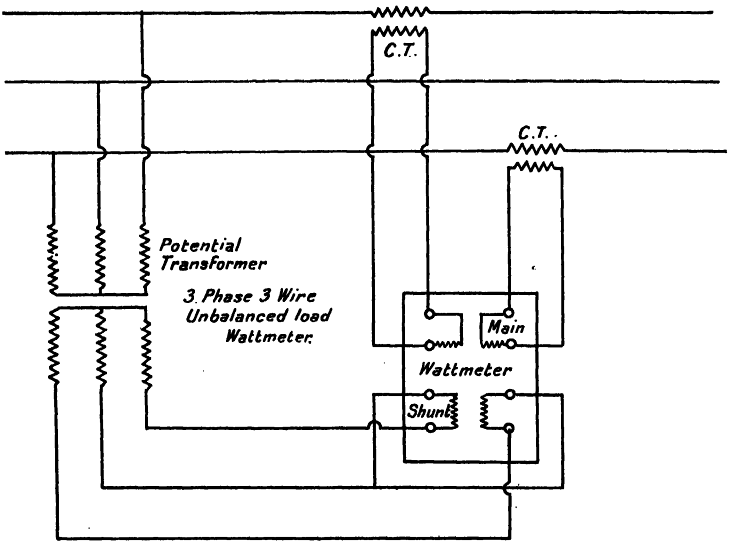


FIG. 60. Diagram of 3 Wire 3 Phase Unbalanced Wattmeter.

a current transformer. Curve B illustrates that up to $\frac{1}{2}$ load the accuracy is within limits and afterwards the errors become large. If a wattmeter is connected to a ring transformer with a small number of ampere turns the usual wattmeter error is, at $\frac{1}{10}$ load, 15 to 20 per cent., and at half load, 4 per cent. Fig. 69 shows the variation of current ratio with change of frequency on various classes of transformers.

Three-phase Integrating Meter.—These instruments record the output of supply in B.O.T. units and consist

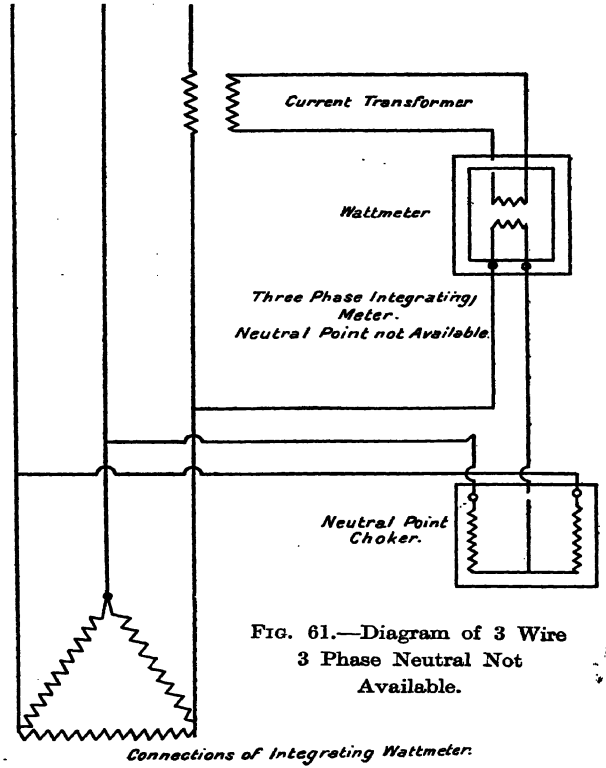


FIG. 61.—Diagram of 3 Wire 3 Phase Neutral Not Available.

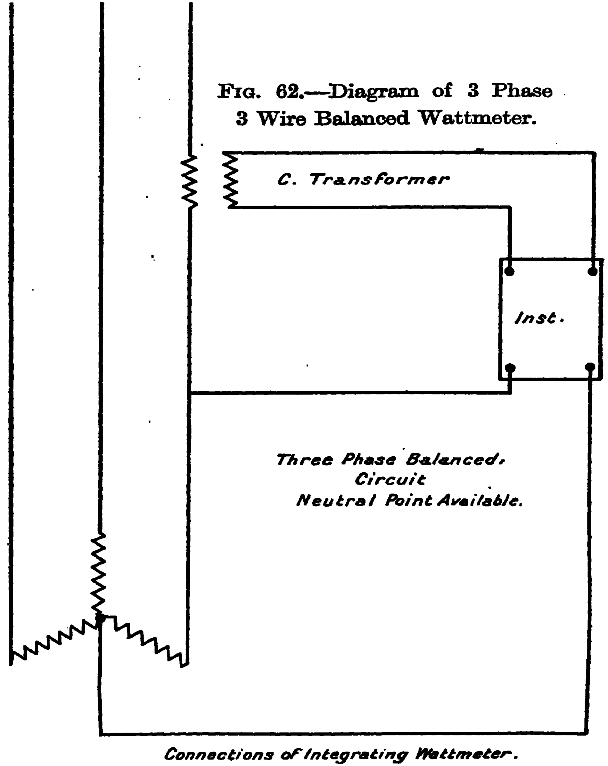


FIG. 62.—Diagram of 3 Phase 3 Wire Balanced Wattmeter.

mostly of two single-phase meters in one case, that is, two motor elements placed diametrically opposite acting upon one disc, the retarding magnet being in this case considered

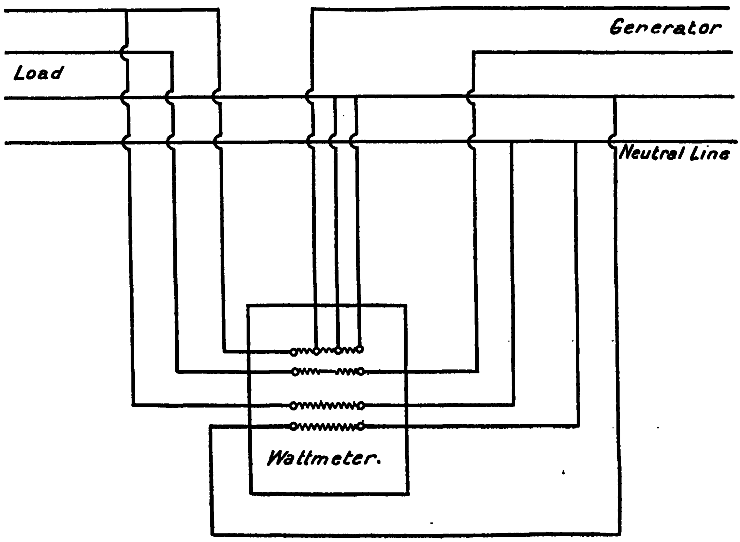


FIG. 63.—Diagram of 3 Phase 4 Wire Unbalanced Wattmeter.

a separate unit. The windings are shunts and series; when the former is excited radial currents are produced in the disc between the poles the directions of which are outward and

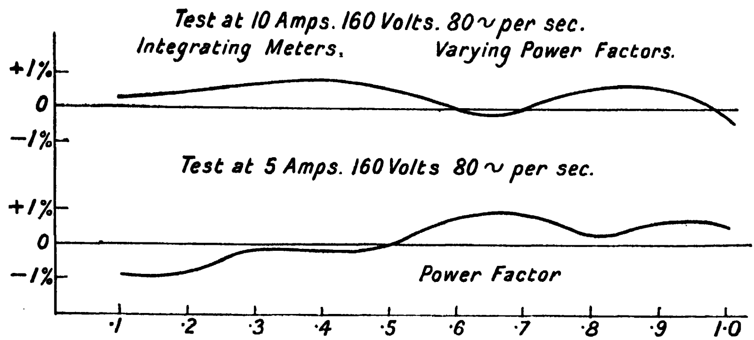


FIG. 64.—Tests of Wattmeters.

inward alternately. The series magnet poles produce fields above these radial currents alternately upwards and downwards, with a result that the torque produced by each pole on each radial current is in the same direction; during

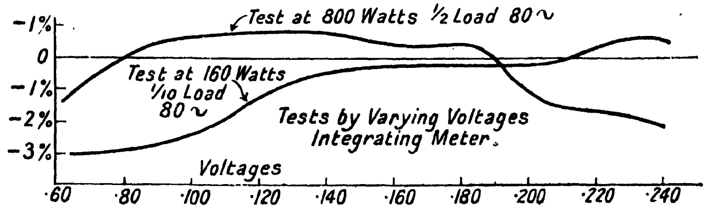


FIG. 65.—Tests of Wattmeters.

the second half period the torques are in the same direction, since both the radial currents in disc and the series flux are reversed. For non-inductive loads eddy currents are exactly in phase with the series flux, and as the shunt flux is in quadrature with the shunt E.M.F., which is due to

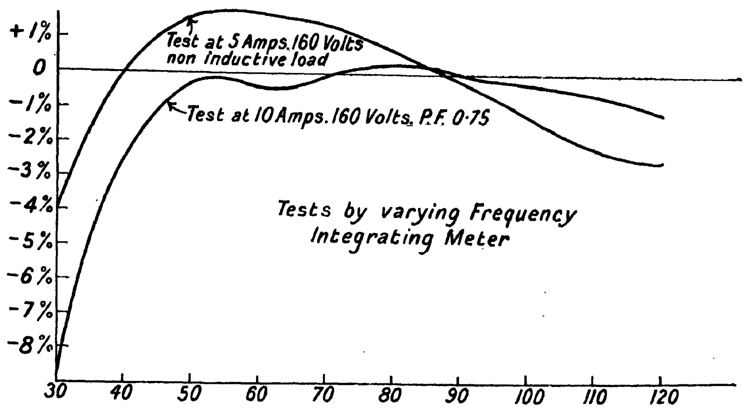


FIG. 66.—Tests of Wattmeters with Varying Frequency.

the high inductance of the shunt magnets it follows that disc eddy currents are in phase with the E.M.F., which renders the accuracy consistent on inductive loads. In order to follow clearly the action of an alternating current meter

we refer to Fig. 70A (3A) showing the electro-magnet windings. The upper electro-magnet is wound with series coils in and out through the five slots. The lower electro-magnet

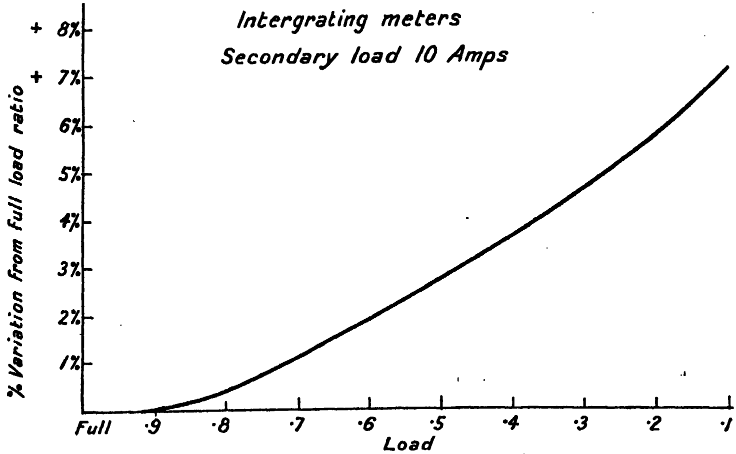


FIG. 67.—Tests of Accuracy of Wattmeters.

is wound with a shunt coil, through which a very small proportion of current is passed, and may be regarded as a current essential to the proper working of the meter only. The series currents magnetize the upper poles, north and

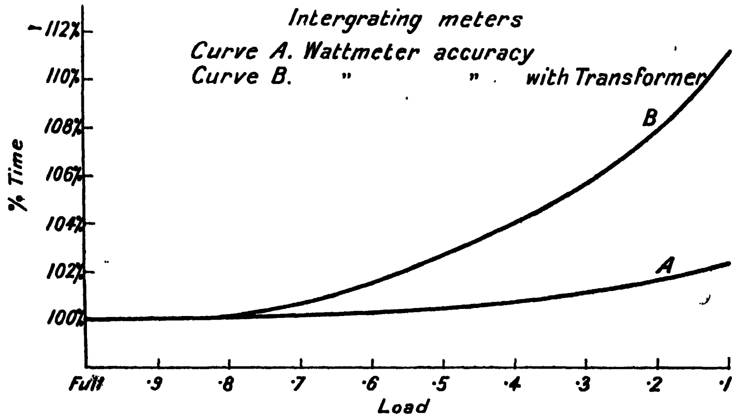


FIG. 68.—Tests of Accuracy of Wattmeters.

south, as indicated on 4A when the series current is in a positive direction as indicated by the upper portion of diagram 8A, which is maximum at time I. The magnetism due to

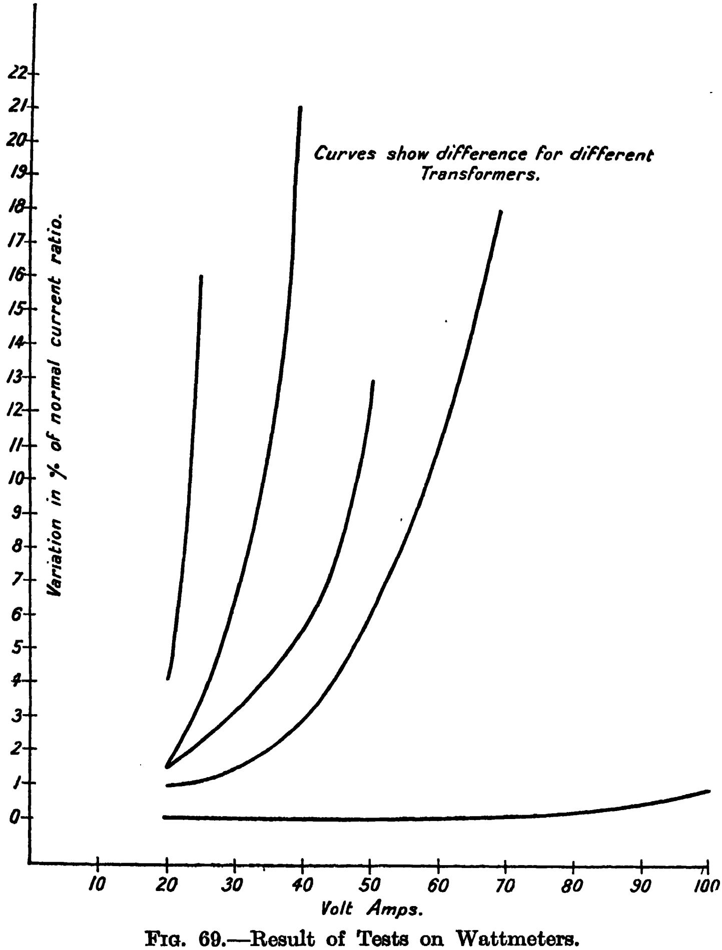


FIG. 69.—Result of Tests on Wattmeters.

the shunt current is zero. As time advances to position II., 9A, the magnetism of the upper poles is zero, while the magnetism of the lower poles is maximum at this instant (see 5A and 9A). From time II. to time III., 10A, the

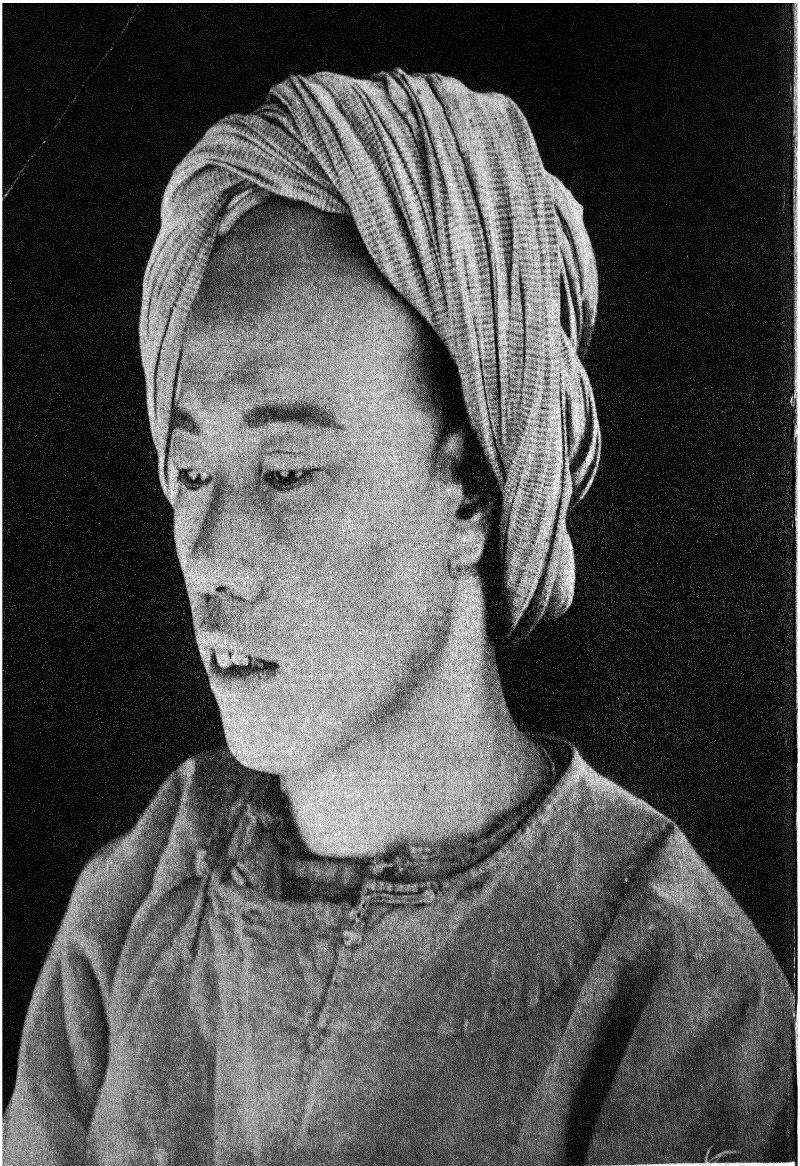


PLATE 10

MONGOLOID

Chinese coolie. (The tooth formation is not a "racial" character, but suggests malnutrition.) This, with the three preceding photographs, illustrates the variety of types within one of the major groups in which men are classified

meter up to 250 volts is 0·03 amperes, with a full load drop of 0·5 volts. When the voltage of supply exceeds 500

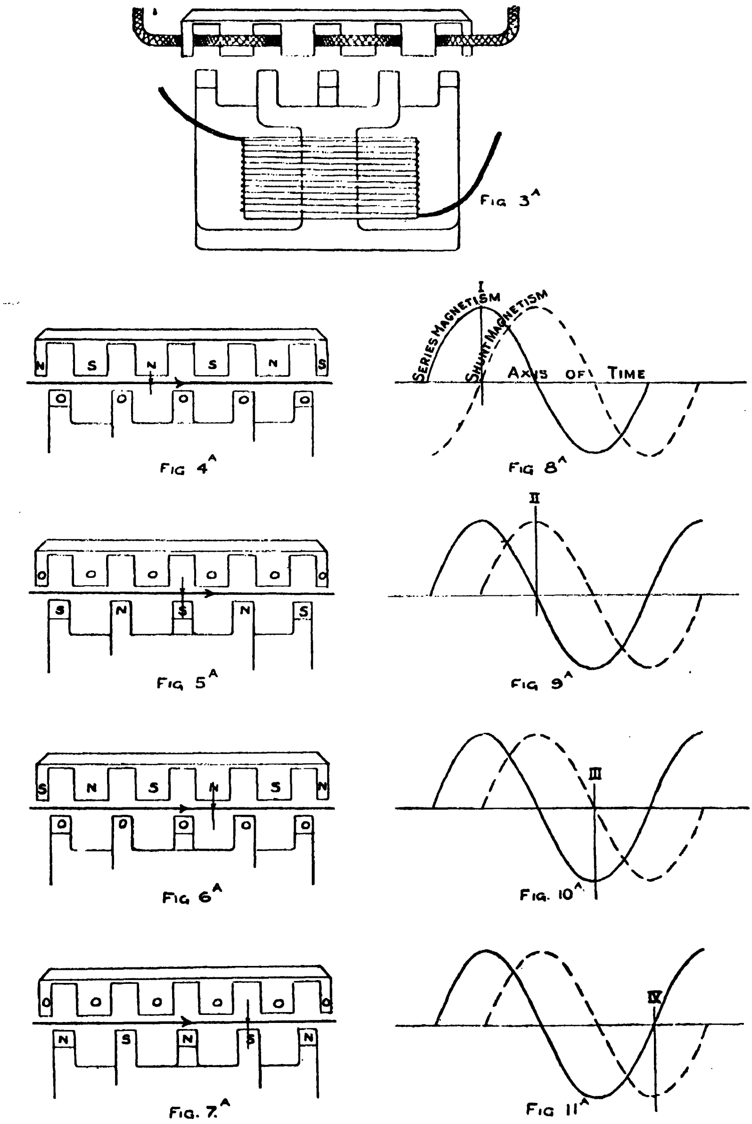


Fig. 70a.—Wattmeter Movements.

per phase and for currents over 100 amperes, current and potential transformers are used with the motor coils connected in series with their secondaries.

Single-phase Meters on Two-phase Circuit.—One of the most common errors in practice is that of measuring two-phase currents by two single-phase wattmeters, for the reason that on high loads at low power factors the two phases are unbalanced to such a degree that in the case of a motor supply, this, together with the transforming action of the motor, tends to retain the power in the line, with the result that possibly one meter will run backward. To obviate this a two-phase meter should be similar to a three-phase meter, or so connected that the readings should comprise the algebraical sum of the two phases and take care of phase difference due to lagging or leading currents.

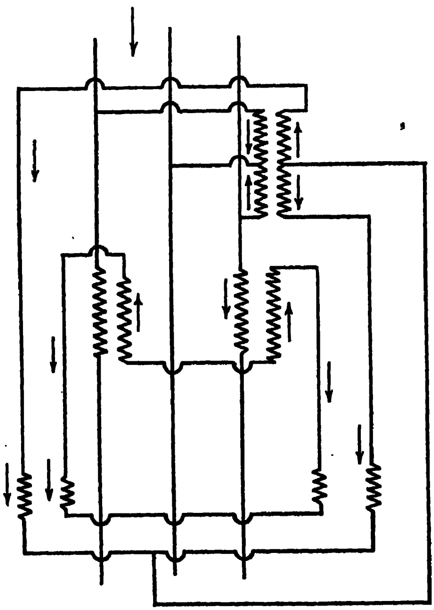


Fig. 71.—3 Phase Meter Connexion.

Single-phase Meters on Three-phase Circuit.—If a single-phase meter is installed to register the output of a three-phase circuit (if the load is balanced), the potential transformer should be connected across the two outer phases with the current transformers forming a reversed V connexion, which is, in this case, similar to a delta connexion as one circuit only is dealt with, or otherwise the potential transformer may have a reversed V connexion, the E.M.F.

being 1·732 which will be in phase with the current. It is necessary when two S.P. meters are measuring three-phase output, that the series transformers be placed in the power line, so that the direction of power in both the potential circuits and the current circuit shall be in the same direction and thus indicate the power as the algebraical sum of the two readings (see Fig. 71).

Instruments.—Ammeters and voltmeters in A.C. work represent values of a different character to those used for D.C. currents, inasmuch as the quantity registered for the former is the "square root of the mean square" value, defined briefly R.M.S. It is often important to know the instantaneous maximum value or the amplitude factor, so that strains, etc., are known, which data is obtained by plotting out curves or by special instruments for that purpose. As far as useful work is concerned the R.M.S. indications serve the purpose. Potentials are measured in various ways, electrostatically or by movements governed by hot wire principles. The latter type depends for its indication on the heating effects, and owing to its small inductance the current is in phase with the P.D. and is at any instant equal to the quotient of the P.D. by the resistance of the instrument, so that the R.M.S. volts will produce R.M.S. currents equal to continuous current, giving the same deflection on either continuous or alternating current, of the same value. The indication of the electrostatic voltmeter is proportional to the square of the P.D., its indication being similar. Electro-dynamic and electro-magnetic voltmeters, owing to the induction of the coil and its variation with inconstant frequency, should be provided with a non-inductive resistance connected in series with the voltmeter coil, so that its impedance equals its resistance. Many measures are adopted for this; usually, however, the meter readings are affected by changes in frequency, etc., unless provisions for compensation are incorporated.

Induction Instruments are another class of meter whose movement consists of an aluminium disc, the contour of which is a volute. This disc, together with the pointer, is mounted on one shaft and acted upon by an electro-magnet, which is shaded by bands of copper, thereby producing magnetic phase displacement, which displacement induces current in the adjacent disc, and the reaction between these currents and the displaced field produces torque, tending to rotate the disc. As before mentioned, these instruments have a non-inductive coil to compensate for frequency and temperature errors. Since the torque varies as the square of the current, so the shape of the disc is such that less of it may be within the field when maximum current is flowing, thus the deflection of the pointer is directly proportional to the current. Temperature errors are compensated in practically the same manner as the frequency, that is, the magnetizing-coil is wound on an iron core and so constructed that the resistance is low and inductance high, and these, together with the non-inductive resistance connected in shunt, serve to divide the current into two paths, one inductive, the other ohmic. If the frequency increases a large proportion of current will pass through the ohmic path, and proportionately less through the inductive path; thus less current passes through the meter coil, but will be equally effective in producing torque on account of the increased frequency. In regard to temperature error, an increase of temperature increases the resistance of disc, thus reducing the current in it, so a greater current will flow through the magnetizing coil; this current tends to increase the torque and balances the reduced current in disc.

Frequency Meters indicate cyclic changes of a quantity apart from potential or current values, which changes are so active that they cannot be observed by potential meters. Their indications are dependent upon the sensitiveness of vibrating reeds which are each tuned to respond only to a given frequency. These reeds are placed

under the active influence of a magnet energized by a potential which must as far as possible be constant, as fluctuations may result in inaccuracies. Cyclic changes can also be indicated by the change in impedance, produced in inductive circuits by varying frequency, by an ammeter connected in circuit with an impedance of known value across a definite potential. When the potential and impedance are known, the frequency can be obtained by calculation. In some cases the instrument is scaled to frequency, the potential being corrected by a compensating device. This instrument consists of an operating element in series with an inductive resistance and a retarding compensating element, together with a non-inductive resistance, so that the operating element and retarding element vary in the same ratio as voltage and frequency.

Idle Current Ammeters.—In many instances these are called for, and their function is to measure the difference between the total current and the load current, graphically represented by a right angle triangle, the two known quantities right angled and the third side representing the "Idle current."

$$\text{Idle current} = \sqrt{(\text{Total current})^1 - (\text{Load current})^2}.$$

Take, for example, a 6,000 watt transformer of the open magnetic type which is found to take a primary current of 1·194 amperes across 2,400 volt mains, secondary open, the true watts being 151. The apparent watts in this case are equal to 2,400 × 1·194 = 2,866 watts, so the power factor would be $\frac{151}{2886} = 0{\cdot}0527$. The problem is to introduce a condenser that will render the power factor unity. We therefore get the total current, 1·194 amperes; the load current is $\frac{151}{2400} = 0{\cdot}0629$; thus as $\text{Ic}\sqrt{\text{Tc}^2 - \text{LT}^2} = \text{Ic} = \sqrt{1{\cdot}194^2 - 0{\cdot}0629^2}$

= 1·192 amperes, then the condenser has to take 1·192 amperes at 2,400 volts.

The Effects of Weakening the Field for Parallel Running.—Let us suppose that in the case of a synchronous motor the excitation has been so adjusted that the armature current is in step with the E.M.F. Weaken the excitation, then a stronger current will flow through the armature with its E.M.F. diminished. The motor will then tend to accelerate with the current out of step with the E.M.F., and its E.M.F. will pass through zero before the current. The more the field is reduced the larger will be the current for a given torque, the E.M.F. being out of step, and further weakening will bring same gradually out of synchronism until the machine stops. Decreasing the excitation causes the E.M.F. to be exactly opposite in phase to the current. What is the effect on the motor of increasing its excitation? The current and torque will be reduced with the E.M.F. increased, so the motor will be momentarily retarded, and this will be accompanied by a reversal of current which will tend to weaken the field before the E.M.F. has reached its zero point, and such will counteract the effects of increased excitation. We see therefore that the current in the armature depends upon its excitation. With a weak field the current is large and with a strong field the current diminishes. The circumstances in the case of the motor (synchronous) are relatively the same with paralleled alternators, and the foregoing remarks serve as an introduction. The advantage of paralleled alternators is that as the load increases the motive power may be increased without causing any fluctuations on the system. While it may be easier from an attendant's point of view to use machines each connected to its own set of bars, the circuits to which the load is connected must suffer from the effects of changing over to the bars which are to relieve them, conditions which would not be tolerated in many cases. As we have already discussed the technical points in connexion with the characteristics of

alternators, it is proposed to explain in simple language, the effects of excitation in connexion with same, and the parallel case given above. There is a difference between synchronous running and successful parallel working, as it is obvious that machines can be run in synchronism without each machine contributing its equal share of the load. This may appear quite elementary, but it is very prevalent in power stations, and the alternators must be switched into circuit with care and each take up its load immediately and be kept in exact step with the other machines. The excitation current is adjusted so that the E.M.F. of the open machine is higher than that of the others and there must not be an interchange of current which modifies the P.F. of the different sets. A retardation of one machine will produce a lagging E.M.F. in the other sets, and the resultant E.M.F will produce a current which is almost in quadrature with the E.M.F. of the machine. This current affects its excitation, and will tend to weaken same. Conversely the acceleration of the machine will produce a current which will strengthen the field. The E.M.F. is therefore increased and also its load. Thus we get transfer conditions which require careful manipulation and which, due to the exigencies of the case, should be adjusted more by independent governors than by the manipulation of excitation. The problem is purely a mechanical one and is entirely dependent upon the ability of a machine to maintain a constant torque. Nearly all the troubles experienced with parallel running of alternators can be traced to the mechanical side of the set for which the designer of the electrical machine has to take the responsibility.

Measurement of Energy on A.C. Circuits.—Diagrams and data concerning the measurement of electrical energy are given in the earlier pages of this book, and in comparison with other matters the subject has received very little attention, being considered of secondary moment. The measurement of energy at the power station

is totally different to the measurement of energy on the consumer's side and admits of wide variations, principally governed by tariffs or by the system on which the consumer is charged. The measurement of electrical energy corresponds with the energy put into the prime mover, which is a minor portion of the total charges on the station, or in other words, its coal bill. Hence from a consumer's point of view where there is a small demand, the accuracy of a meter is not an important matter, and is much better dealt with by charging a round figure per quarter with a meter that will indicate approximately the value of such charge instead of burdening the commodity with heavy rents and money lying idle, to secure accuracy, especially when we know that 75 per cent. of the charges are estimated. It is quite easy to construct a meter for a few shillings, for instance, that will indicate the amount of current within, say, 5 per cent., whereas accurate meters cost thirty-five shillings and upwards according to size and are paid for by the consumer many times over. The question of the measurement of energy from a station point of view is different, and in order to correctly understand its value some technical observations are necessary. Consider a two-phase circuit connected independently; the power may be measured by a meter in each circuit. The sum of the two readings gives the total power in the two-phase circuit. If the circuit have one cable common, the same system may be employed, but these elements must be interconnected because in the case of a motor the phases may be so unbalanced and the power factor so affected that the sum of the readings would be less than the actual energy, the motor acting as a species of transformer. If the system is absolutely balanced the single elements of the meter need not be interconnected. In the case of a three-phase circuit, star connected, and the neutral point available, three wattmeters may be used with the shunts connected to the star point, the sum of which will give the total power in the

circuit. When, however, the system is mesh connected and it is possible to introduce the current coil in each of the circuits, the shunts being connected across its terminals, the sum of the three wattmeter readings will be the total power in the circuit. This latter connexion is very rarely used. As in many cases the neutral is not available it is often the practice to artificially create one by the use of three non-inductive resistances, the shunt coils of the meter being connected across this artificial point and the readings of the meters will be as before where the neutral point is available. The use of two wattmeters to measure the output of a three-phase circuit is often adopted, when the current coils are in circuit on the power mains with the shunt coils of both meters connected across the phases, and is consistent with the data already published on the subject as represented below.

Star Coupling Equation, Instantaneous Valves.—

$$W = V_1C_1 + V_2C_2 + V_3C_3$$

There is also $\quad C_1 + C_2 + C_3 = O$

as $\quad C_3 = -C_1 - C_2$

V = pressure.
W = energy.
C = current.

For power we get

$$W = (V_1 - V_3)\ C_1 + (V_2 - V_3)\ C^2.$$

Assume the current in the circuit passes from left to right, acting in a positive manner from the neutral point, with the P.D. of the shunt coil acting towards the middle phase. One wattmeter (say in phase 1) indicates the mean value of the product $(V_1 - V_3)\ C_1$. The other wattmeter in phase 2 will then measure the mean value of $(V_2 - V_3)\ C_2$.

From this the algebraical sum of the readings of the wattmeters represents the mean value of energy of the three-phase circuit. In the case of a mesh connexion the same scheme remaining; V_1^0 representing the instantaneous E.M.F. and V. the P.D. between the mains, with C

representing the currents, r being the constant of resistance.

$$V_1^0 = V_1 + rC_1$$
$$V_2^0 = V_2 + rC_2$$
$$V_3^0 = V_3 + rC_3$$

Thus

$$V_1^0 + V_2^0 + V_3^0 = V_1 + V_2 + V_3 + r\,(C_1 + C_2 + C_3)$$

As

$$V_1^0 + V_2^0 + V_3^0 = O$$

and

$$C_1 + C_2 + C_3 = O$$

so

$$V_1 + V_2 + V_3 = O$$

there being no current in the mesh.

The instantaneous power will be—

$$\begin{aligned} W &= V_1C_1 + V_2C_2 + V_3C_3 \\ &= V_1C_1 + V_2C_2 - (V_1 + V_2)\,C_3 \\ &= V_1\,(C_1 - C_3) + V_2\,(C_2 - C_3) \\ &= V_1C_2 + V_2C_1 \end{aligned}$$

The algebraical sum of the two wattmeter readings represents the energy of the circuit with the wattmeters coupled up in positive direction; this method is for unbalanced circuits. For balanced circuits one wattmeter will suffice. The current coil of the wattmeter is in one phase, with the shunt coil connected across the two other mains, making the middle of such connexion common on the current main.

Taking the same calculations as before we get the instantaneous power as

$$\begin{aligned} W &= V_1C_2 + V_2C_1 \\ &= V_1C_1 + V_1C_3 - V_2C_2 - V_2C_3 \end{aligned}$$

As the circuit is balanced the mean value of V_1C_1 is the same as V_2C_2, so the instantaneous power is

$$W = V_1C_3 - V_2C_3$$

so therefore the wattmeter by its shunt coils will indicate the sum of the total energy of the circuit.

Wattless Component.—If the resistance of the circuit is zero, there is no wattless current. The angle of lag would then be $\frac{\pi}{2}$

and is represented as being in quadrature with the E.M.F. This component is of no value to a circuit, but represents the periodic change of conditions and continues its appearance in consequence of inductance. The displaced E.M.F. relatively to the current curve introduces this component, and modifies it.

Power Factor represents the condition of the circuit as to its E.M.F. and current values. The power of an alternating circuit is, assuming that E.C. represents maximum values, $\frac{1}{2}$ E C cos ϕ,

ϕ = angle of lag,

$$\tfrac{1}{2}\,E\,C = \frac{E}{\sqrt{2}} \times \frac{C}{\sqrt{2}} \text{ R.M.S. values.}$$

$\frac{1}{2}$ E.C. is the apparent watts and cos. ϕ is the factor to obtain true watts.

Harmonics.—An alternating E.M.F wave contains harmonic components of an odd order only, and so long as it is symmetrical can contain no harmonic component of an even order. The function containing odd harmonics is by equation.

$F = A_1$ p.t. $+ B_1$ cos.p.t. $+ A_3$ sin. 3 p.t. $+ B_3$ cos. 3 p.t. + and so on, as represented under Harmonic Functions in the former pages of this book. The presence of a third harmonic depends upon the distortion of the curve; thus the resultant of the two waves when the fundamental harmonic passes through zero position is flattened at its peak. If the curves are at maximum displacement the peak will be pointed. As a simple harmonic is represented by a straight line of a vector, so a complete periodic function which may be regarded as made up of harmonic functions of different frequencies may be represented on a straight line as the sum of projections of the rotating vectors of different frequencies.

The first fundamental harmonic term would rotate with angular velocity P., the third harmonic correspondingly with angular velocity 3 P.; fifth harmonic = 5 P. The differences of angular velocities are proportional to the relative positions. The first fundamental revolves as P, the third term as 3 P, and fifth term as 5 P. During one-third of the fundamental period the first vector will sweep out an angle of $\frac{2\pi}{3}$ 120°, coming into position ·02. Another third of a period will bring it into position ·03 = 120°. If since the resultant of ·02 and ·03 is equal and opposite to ·01 it follows that the sum of the projections will vanish. In the case of the third harmonic, 3 P, it follows that during one-third of the fundamental period the vector will trace out an angle of $3 \times \frac{2\pi}{3} = 2\pi$. The same reasoning will apply in the consecutive positions of the rotating vector as also in the fifth term 5 P, the sum of their projections being zero 120° apart; the seventh term ditto. The ninth term has three coincident positions with a sum of the projections equal to three times the projection at the instant referred to. So harmonics expressed by a multiple of 3 have three coincident positions, while harmonic terms not a multiple of 3 have three positions 120° apart, as explained by a well-known authority.

If a given complete E.M.F. or current wave consisting of a positive and a negative half wave be divided into three parts, and the parts be superimposed and their ordinates added together, then the resultant curve will contain all the harmonics which are multiples of 3 with their amplitude magnified three-fold and will contain no other harmonics.

If n is the order of the harmonic considered and if n is the multiple of 3, then $\frac{n}{3}$ and $\frac{2n}{3}$ will both correspond to a whole number of revolutions giving 3 coincident positions,

while if n is not a multiple of 3, then $\frac{n}{3}$ will correspond to a whole number of revolutions + $\frac{1}{3}$ or $\frac{2}{3}$ of a revolution and $\frac{2n}{3}$ will correspond to a whole number + $\frac{2}{3}$ or $\frac{1}{3}$ of a revolution respectively, whereby 3 positions 120° apart are obtained.

A flat-top wave is to be preferred to a peaked wave for insulation, as they impose less strain.

A peaked wave is preferred for transformers and this causes a flat-topped wave of magnetic induction with reduced hysteresis loss due to reduced magnetic induction.

PART II

Direct Current Switchgear

CHAPTER V

PARALLELING D.C. MACHINES—PROTECTION—EXAMPLES—PROTECTION OF COMPOUND MACHINES—PROTECTION OF SERIES AND SHUNT MACHINES—CIRCUIT BREAKERS—ARTIFICIAL FIELD CARBON BREAKERS—INDUCTIVE RISKS—MAGNETIC CORE FIELD CALCULATIONS—CHOKING—RESISTANCE OF CONTACT TESTS—PORCELAIN FUSE TESTS—EFFECTS OF OPENING CIRCUITS.

The Paralleling of D.C. Machines.—The difficulties attending this operation are not so pronounced as in the paralleling of A.C. machines, the protection of D.C. machines being an easy problem. There are, however, propositions presented which require a considerable amount of thought. In the case of a large tramway undertaking having compound wound dynamos it was considered necessary to depart somewhat from the standard practice of protection by having overload protection on + and — poles. The switchboard was a two-pole one, with series coils on the positive side of the machine, and the negative provided with an overload cut-out. In order to clear the board of the negative bar and thereby avoid the very serious risk from having gear of opposite polarity cramped up, such bar was entirely done away with and the return cables from the tramway system were grouped together in parallel on a heavy busbar, to which were also connected all the negatives from the machines. At the same time the polarity of the machine was reversed, the series winding then becoming negative. This alteration was followed by a serious accident. One of the machines brush collector rings went to frame and, owing to the series winding being on the negative side, the current

flowing through them to the fault gave sufficient excitation to the machine to maintain the arc, and the only way to

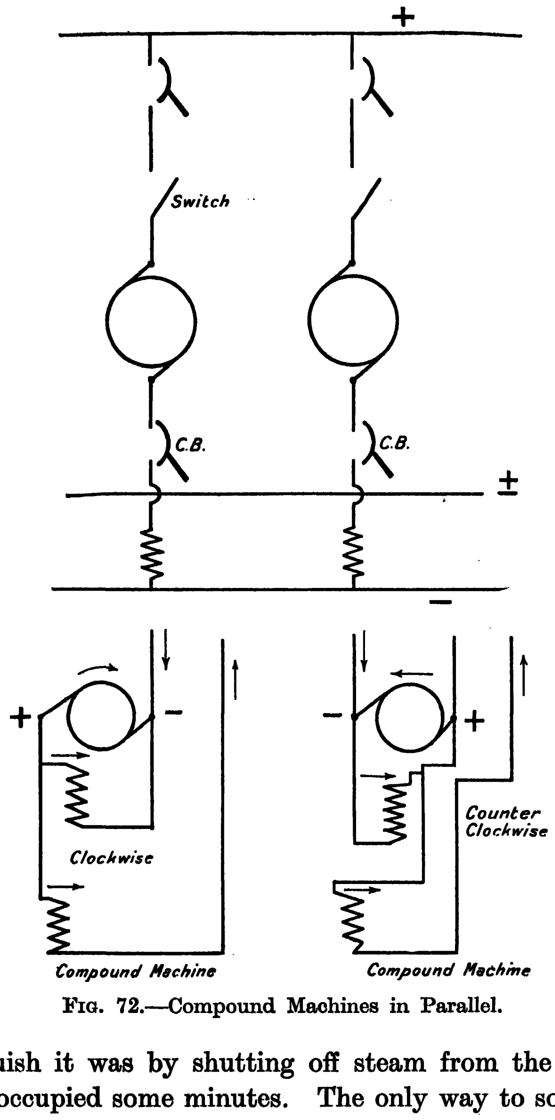


FIG. 72.—Compound Machines in Parallel.

extinguish it was by shutting off steam from the engine, which occupied some minutes. The only way to solve this difficulty was by introducing a circuit breaker between the

negative brush of the generator and the connexion of the series winding (see Fig. 72), from which it will be seen that should the positive side of the machine go to earth without a breaker between the armature and series coils the effect would be that of a series machine on short circuit, and nothing could save a burn out, unless the machine was shut down at once. The replacement of breakers by fuses would again be ineffective, since the negatives are in common through the equalizing bar and a fault developing in one machine would blow every negative fuse of the machines in circuit. It is usually the practice to provide reverse current protection on all machines that are paralleled so that one machine may not be a short upon another.

Series-Wound Machines.—In the case of series wound machines their voltage would alter considerably, due to load, and assuming that one machine increased its voltage over the other, then the latter machine will supply less current, its armature volts being nearly zero. The result would be that the poles of the machine with volts across armature nearly zero would reverse.

Shunt-Wound Machines.—The effect of shunt machines is almost exactly opposite. The voltage increases on decreasing load and decreases on increasing load. Assuming that the voltages of two machines are not exactly similar the effect would be that the machine at higher potential would give a greater output till the other machine equals it in E.M.F. If, however, the E.M.F. of one machine is such that instead of giving out, it consumes energy, the poles are not reversed but it will run as a motor and overload the healthy set.

Compound Machines.—A reversal of current is a more serious matter since such reversal would flow through the series coil and weaken the magnetism, which is produced chiefly by the shunt coil. The equalizing bar is connected to the poles, to which are also connected the ends of the series winding. If both armatures have the same E.M.F., no current passes through the equalizing bar. If, however,

one machine reduces its potential to that of its neighbour, current will flow through the equalizing bar in the opposite direction to that when supplying current, the series coils being unaffected, the current reversing through the armature alone. These positions have to be considered by the switchboard designer and automatic gear provided to save such occurrences.

Circuit Breakers.—There are two principal types of circuit breaker for D.C. work, those of the magnetic blow-out, and those of the carbon type. The first-named open the circuit and dispel the arc in an artificially-

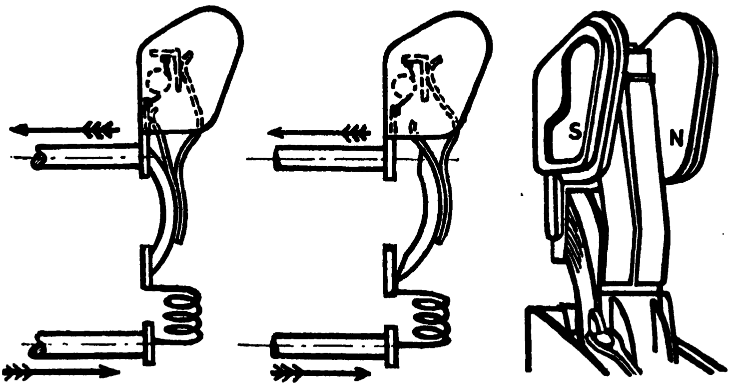


FIG. 73.—Magnetic Blow Out Field.

created field (see Fig. 73). Oscillograph tests shown later record their results in comparison. The introduction of the magnetic blow-out circuit breaker into the field of electrical industry brought with it a host of criticism chiefly in respect to the high E.M.F.'s introduced into the circuit by the rapid opening of automatic cut-out and the induced E.M.F. caused by the artificially created field.

Induced Rises.—If a steady E.M.F. be applied at the end of a conductor of resistance R the current does not rise instantaneously to its full value, as given by Ohm's law $C = \frac{E}{R}$;

it takes time to reach this value, since at the moment when the current starts to flow it brings into existence an opposing E.M.F. depending on the rate of increase and which opposes the rise of current. If the E.M.F. be removed the current sinks to zero, gradually decreasing in strength, for the reason that the current value depends upon the presence of a magnetic field due to it. The rate at which the current dies down is indicated by the angle of inclination of the curves of the oscillograph record, which quantity is called inductance, since it depends on the E.M.F. of self-induction. In addition inductance is also governed by the geometrical form of the conducting path and the amount of iron, if any, in the circuit. The maximum pressure shown on the records is the resultant E.M.F., which pressure rise is the resultant of the impressed pressure and the E.M.F. of self-induction. The E.M.F. of self-induction is $E = \left(-L\frac{di}{dt}\right)$ the algebraical sign depending on whether the current is increasing or decreasing. If the E.M.F. is withdrawn, the current dies to zero, the self-induced E.M.F. tends to assist, but if the current be increased the direction of self-induced E.M.F. is negative or opposed to the increase.

Magnetic Arc Field.—The production of E.M.F. in this field depends on its construction and winding. The total induction in the coil is equal to the number of turns traversed by unit current and affected by the change of strength of the current symbolized $\frac{di}{dt}$. Referring to Fig. 73 the coil is short circuited when the breaker is in the closed position and in series with the line on open circuit. As there is an appreciable time occupied in building-up the field, which is not at its greatest density when the arc is first formed, the turns introduce a choking effect, since the resistance is low, the back E.M.F. assures a high factor ($L\ x\ t_2 \times C$) and ($N\ x\ t \times C$) so that if turns are doubled, the induced E.M.F. is quadrupled, the current being $\frac{1}{2}$. The top position of

the brush leaves contact first, then the first auxiliary, and lastly, the second auxiliary. Between the two auxiliaries a coil is inserted wound round a core of which the two iron cheeks of the blow-out form the pole pieces. Immediately before the second auxiliary breaks circuit, the blow-out coil is inserted, and creates a magnetic field across the two pole pieces of the blow-out. The second auxiliary is arranged so that the arc formed on breaking circuit is in the centre of the field. The lines of force between the pole pieces oppose the field formed by the arc on breaking, and the arc is forced upwards and downwards, depending upon the direction of the winding of the blow-out coil. Assuming the current enters at the bottom of the breaker, the coil should be wound so that the pole pieces are magnetized as shown in Fig. 73. The arc will then be forced upwards, no matter which way the current flows through the breaker. As the main brush has to carry the main current continuously, it is essential that its contact area should not be damaged by the arc on opening circuit, and it is to prevent this that the first auxiliary is used. With a heavy current rupture there is a slight difference of potential between the second auxiliary and the main brush due to the ohmic resistance of the blow-out coil, and the point of contact. The first auxiliary takes the arc formed by breaking this difference of potential.

Resistance of Carbon Contacts and Magnetic Blow-Out.—In the table below particulars are given of the resistance between the carbon contacts of a breaker and for the sake of comparison with magnetic blow-out breakers, which include the resistances of the blow-out coils. It will be seen that the carbon contact is relatively of very low conductivity; with moderate currents this is not a serious consequence, but with heavy currents such as short circuits some burning of the main brush is difficult to avoid; on that account metallic contacts for the auxiliary are not to be recommended as a general rule.

	Carbon Break.			One-turn Magnetic Blow-out.		
Drop of volts	4·5	3·45	1·85	1	0·7	1·1
Resistance in ohms .	·0232	·0196	·0185	·101389	·0014	·001198
Current in amperes	204	176	100	776	500	920
	Three-turns Magnetic Blow-out.			**Six-turns Magnetic Blow-out.**		
Drop of volts	1·2	·95	·725	1·475	1·15	·74
Resistance in ohms .	·00133	·001532	·001775	·00175	·00221	·00179
Current in amperes	900	620	708	840	650	415

Enclosed Fuses.—The accuracy of a fuse depends on the care with which it is designed. It is not difficult to make a fuse which is within 10 per cent. of its rating. The great difficulty in the enclosed fuse is the difference in the overload blowing time. When a fuse is put into circuit and after it has been in circuit for some time, due to the fact that the heat conductivity of the porous metal which is immediately in contact with the metal of the link, the time rapidly decreases as the temperature rises. To overcome this, less sectional area is provided in the centre of the link so as to get a high current density with a large volume of air, so that the heat generated by the rise of current can be dissipated. Many methods are used for getting rid of the metallic vapour, and it is essential that such provision should be made, or cracked and burst porcelain holders will result. Fig. 74 records an oscillograph test of this type of fuse breaking a current of 800 amperes; it will be seen that, as there is a tendency to fit fuses in place of breakers there is a delayed opening of the circuit due to the release of the metallic

vapour. Ample provision should be made for circulation of air.

Fig. 74.—Oscillograph Tests of Porcelain Fuses.

Test of Breakers.—Figs. 18, 19 and 20 show the diagrammatic arrangements of the tests given below, the nature of such tests being equivalent to the ordinary uses of breakers supplied to the market. The following four tests were taken on a magnetic blow-out breaker at predetermined loads wound with 6 turns of blow-out coil (strong field). The volts across circuit breaker at the moment of rupture vary from 112 volts at 440 amperes to 187 volts at 1,050 amperes. The time occupied in completely interrupting the circuit in the case of the 1,050 ampere test was 0·066 seconds, and of this 0·058 seconds was occupied in the operation of the mechanism of the breaker to the stage of commencing to open the circuit and only 0·008 second in blowing out the arc formed at break.

Tests 27 to 30 were made with magnetic blow-out continuously maintained. The excrescences are practically in proportion to the load ruptured.

The three following tests, Fig. 74B (31, 32 and 33), are with a breaker of the artificial field type, having the overload coil creating a medium field at the point of break. The rises of E.M.F. are less than in the case of 27 to 30, and the arc was dissipated in a more positive manner. The currents, how-

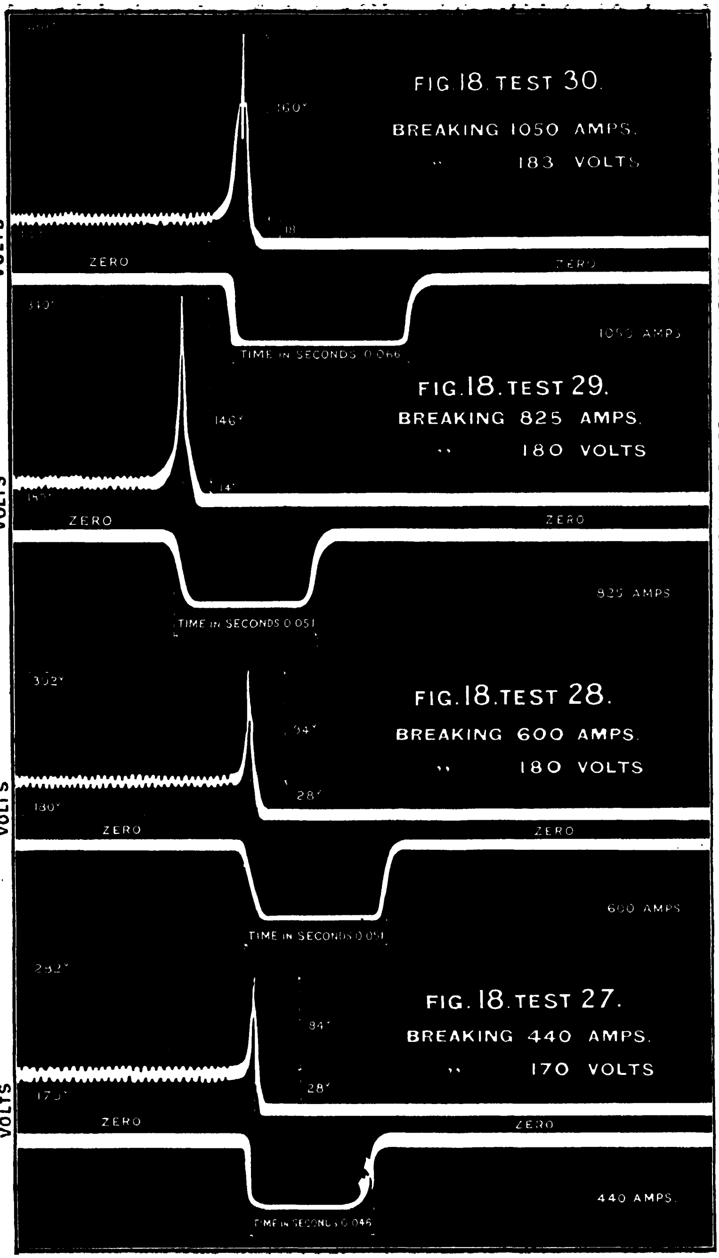


FIG. 74A.—Tests 27–28–29–30. Tests on Magnetic Blow Out Breakers.

ever, are small, but comparison can be made with the other forms of breaker at these values. Fig. 74c (34 to 37) inclusive are taken on the carbon break circuit breaker. The pres-

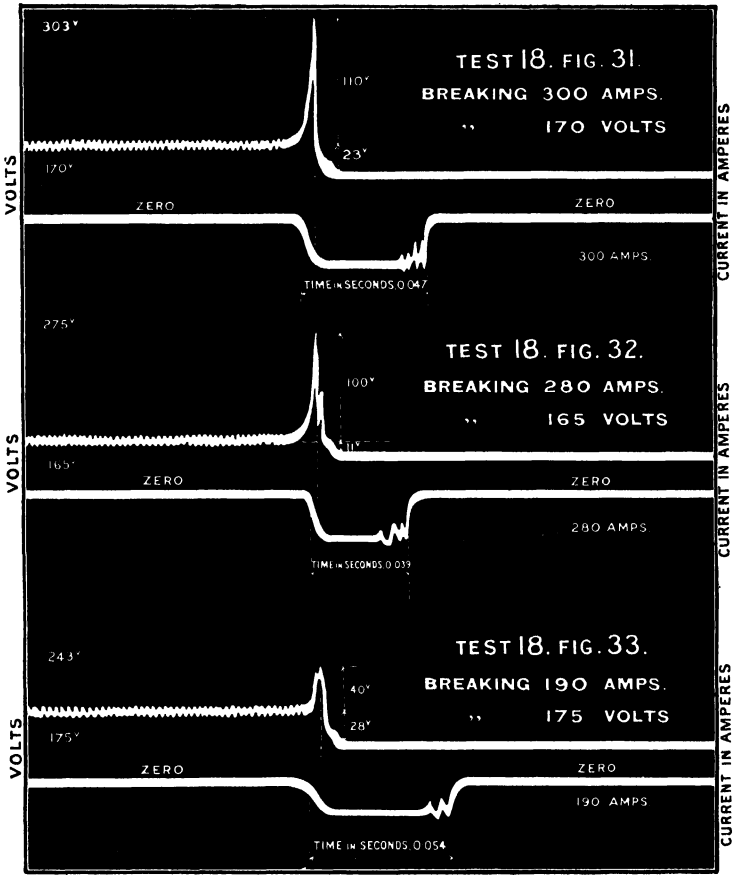


FIG. 74B.—Tests 31 32 33. Tests on D.C. Breakers.

sure rise is relatively low at break and the time taken in the disruption of the arc is relatively longer. The time taken in operating the mechanism is irregular, which does not appear to be a function of the current, as might be antici-

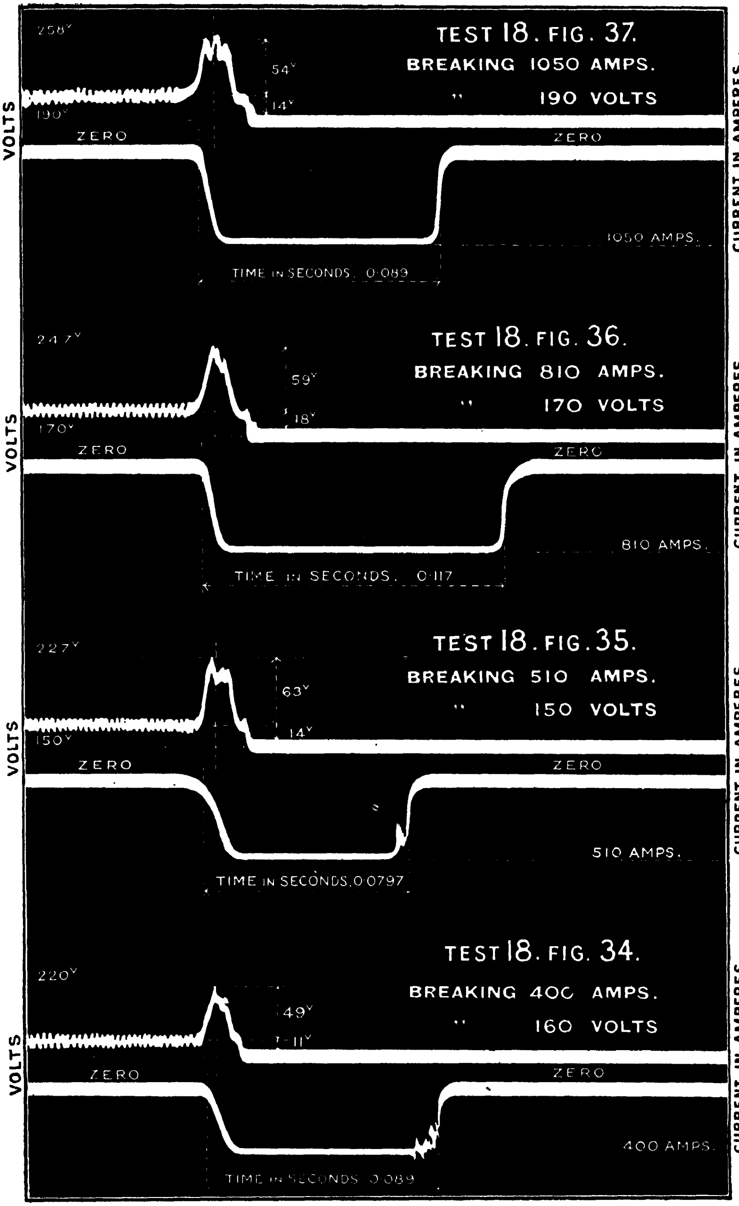


Fig. 74c.—Tests 34–35–36–37. Tests on D.C. Breakers.

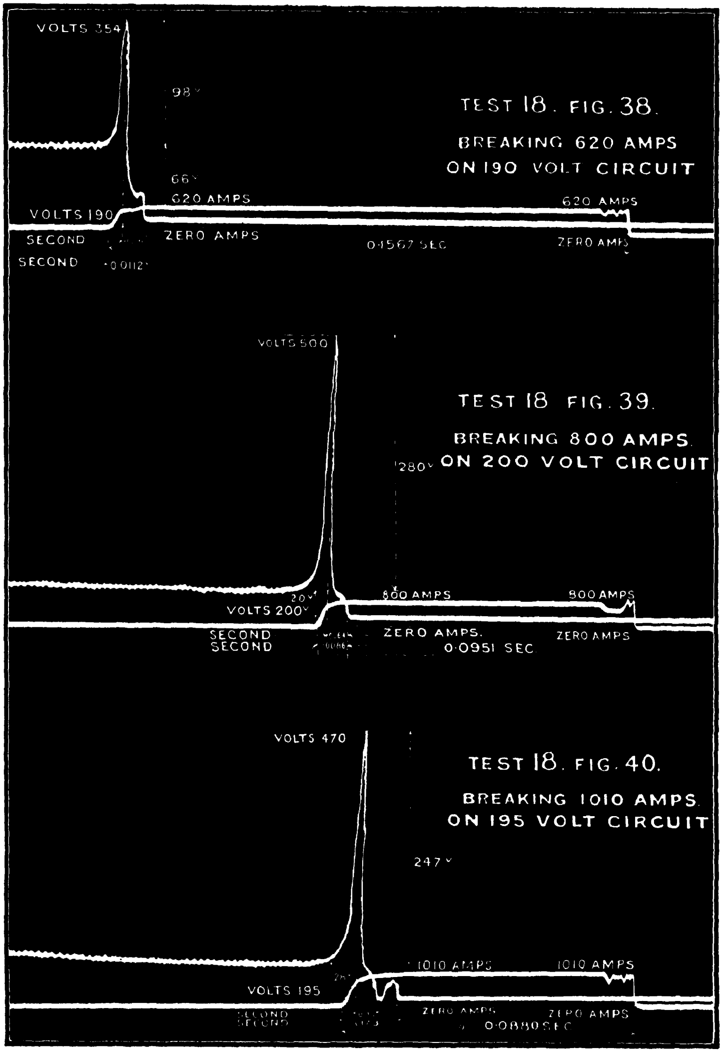


Fig. 74d.—Tests 38–39–40. Tests on D.C. Breakers.

pated. The explanation of this may be, that the toggles might not have been fully closed in every case. At 1,050 amperes the pressure rise at break was 68 volts as compared with the oil breaker at 990 amperes with 99 volts and 178 volts at 1,050 amperes of the magnetic blow-out type. The absence of the rapid rise at the moment of disruption of the arc is particularly noticeable in this breaker in comparison with its neighbours.

The next three tests are taken off a magnetic blow-out breaker of the weak field type, and it was expected that less rise of E.M.F. would present itself in comparison with those of the strong field type. There is, as will be seen by reference to Fig. 74D (38, 39 and 40), some irregularity in the relation of the different tests which is no doubt due to the unstable conductivity of the arc formed at the intermediate contacts, at the separation of which the arc is diverted through the field exciting coil. The idea that actuated the design of this weak field was to prevent large rises of E.M.F. on short conditions. In order to obtain this desirable result it is necessary to give the breaker a wide, quick field, or it will not disrupt small currents. The strong field appears to be less effective than those of the weak field wide break.

Fig. 75 shows the average results of all breakers tested with their E.M.F. rises and time of disrupting the arc.

Test 19, Figs. 75A–K, shows the oscillograph results of the various forms of breakers opening on direct current shorts. The results, time of operation, are plotted out in these curves and are remarkable for the short time occupied in effecting rupture. These curves are actually produced by the effects of opening such a circuit, and as they cover current values up to 6,500 amperes at 500 volts they should prove of great service for the guidance of designers.

It may be said that these tests were only secured at great expense and trouble, the author having to wait for a period of nearly six months during this investigation in order to

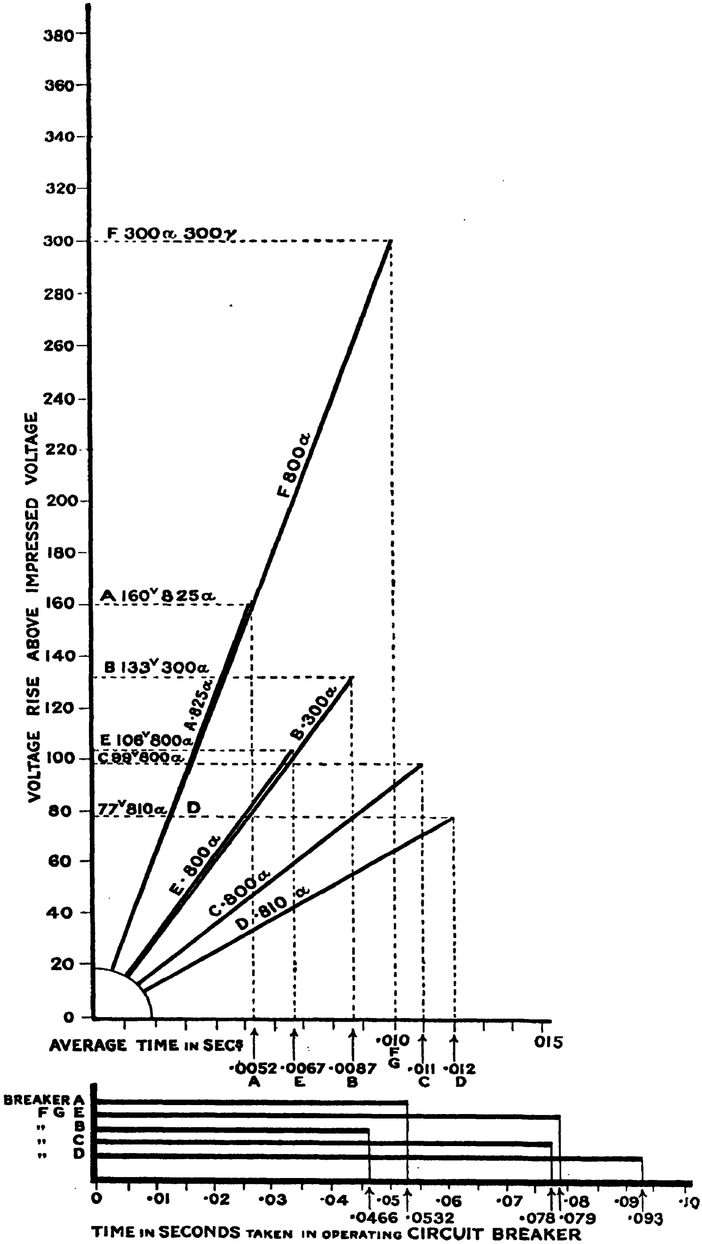
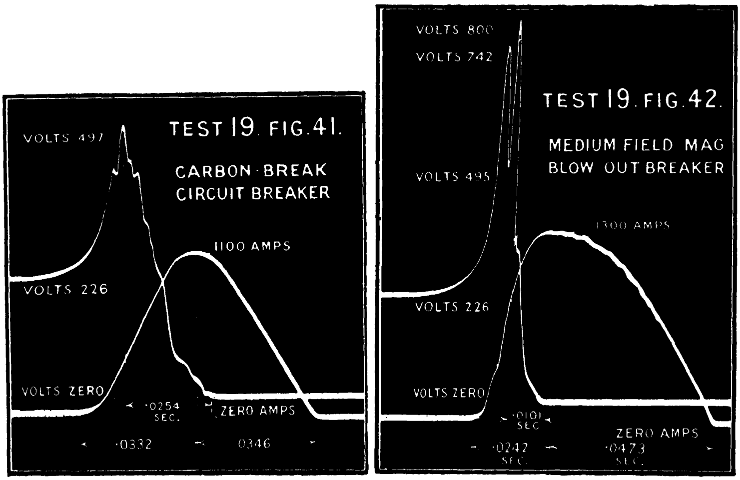


Fig. 75.—Comparative Results of Breakers.

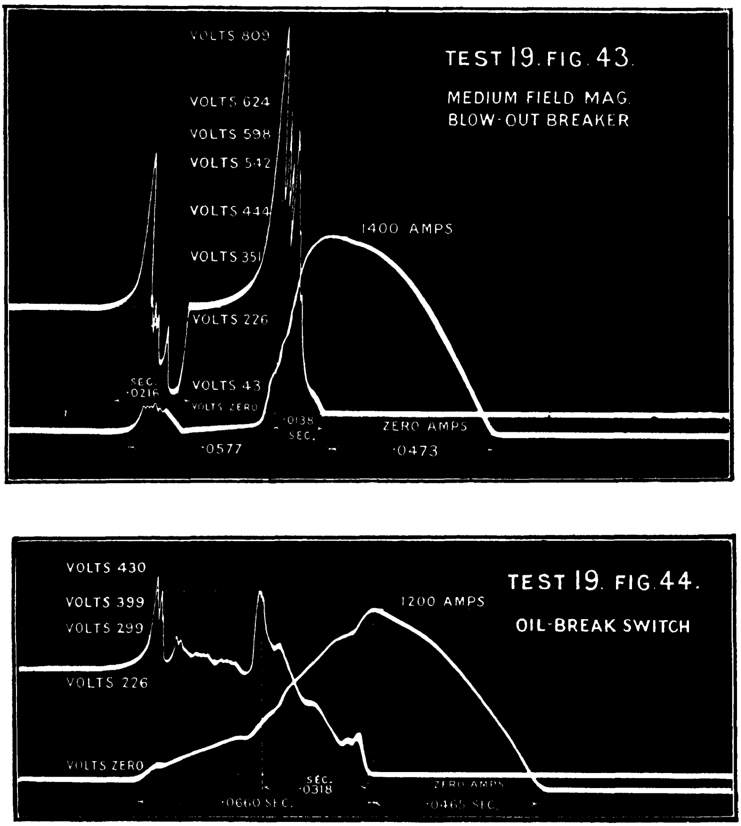
secure the necessary load. There is no doubt that research of this character repays for any inconveniences suffered, as the result cannot be disputed. The characteristics of the various forms of breakers were particularly noticeable in opening these heavy shorts. The strong field magnetic blow-out breaker made a terrific noise with a highly intensified arc. The carbon break gave rise to an arc of much longer duration and quite capable of setting fire to apparatus in its immediate neighbourhood, whilst the contacts



TEST 19.—FIG. 75A and 75B. Test on D.C. Breakers.

were all sadly burnt and the mechanism thrown out of gear. The oil switch opened very quietly, but the oil switch tank burst in the first test, a much stronger one having to be substituted, and provision made for the release of the gases formed on rupture. The auxiliary contacts were melted and the wood lining burnt. The experiences gained at these tests were that robust construction and mechanical efficiency were of paramount importance and that ordinary calculations of current densities and contact area were of

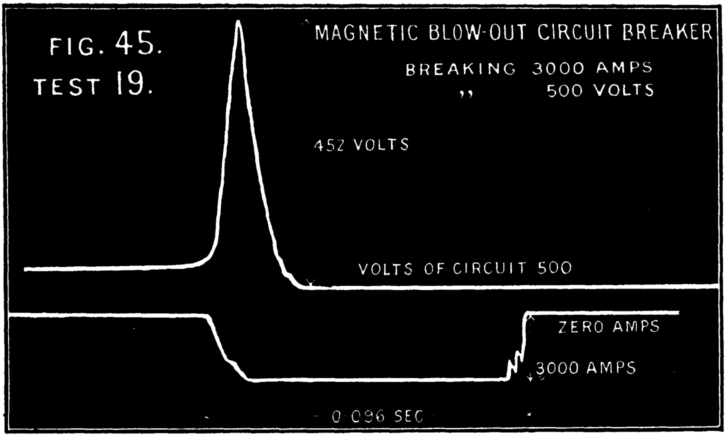
little consequence in dealing with such violent ruptures. It was also found that for the final breaking of such loads, carbon contacts were of no use, having to be reinforced with copper faces. In a discussion on the question of robust

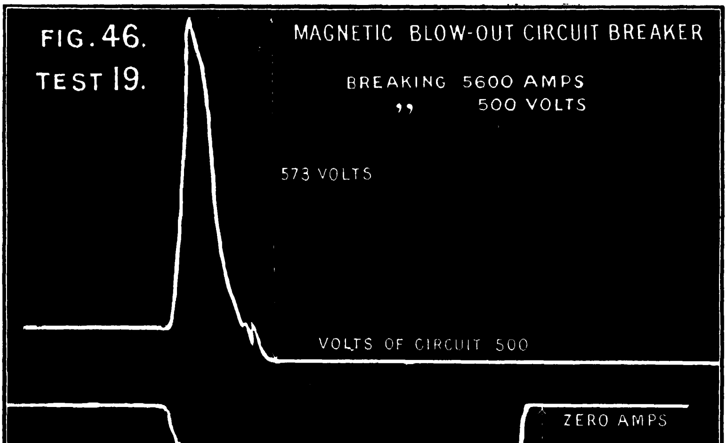


Test 19.—Figs. 75 c and d. Test on D.C. Breakers.

construction in America it was argued that it was false economy to buy a breaker for a heavier duty than its current rating, and that the cheaper the breaker the better for all parties interested, since the replacing of

such breakers was a very desirable asset to a company manufacturing same. As the success of a supply depends

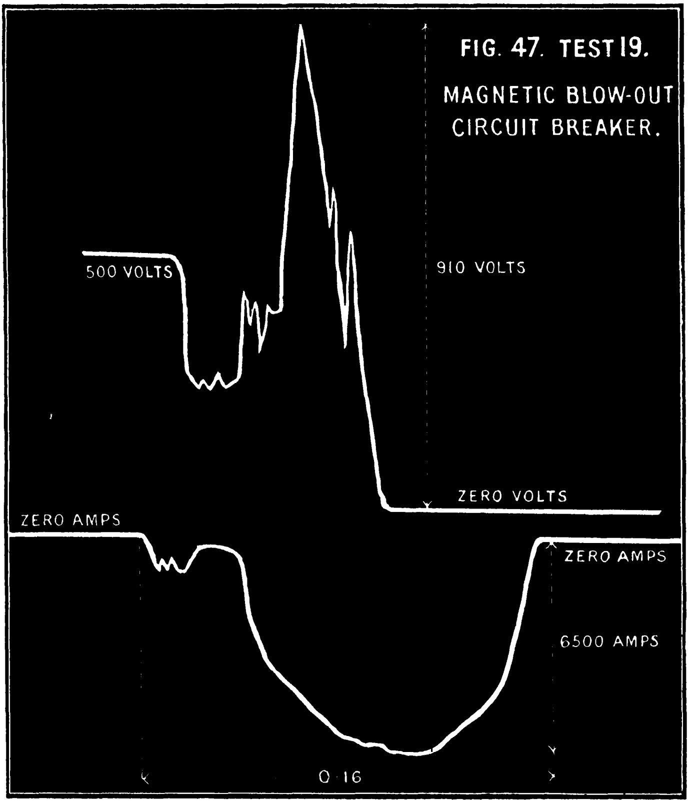




TEST 19.—FIG. 75 E and F. Test on D.C. Breakers.

upon the reliability of such gear, this, however, appears false economy.

Heavy Capacity Fuses.—It has been the practice in this country when currents exceed say 750 amperes, not to enclose the fusing metal in a porcelain holder, but either to attach the fusing metal to a protective bridge, or to supply

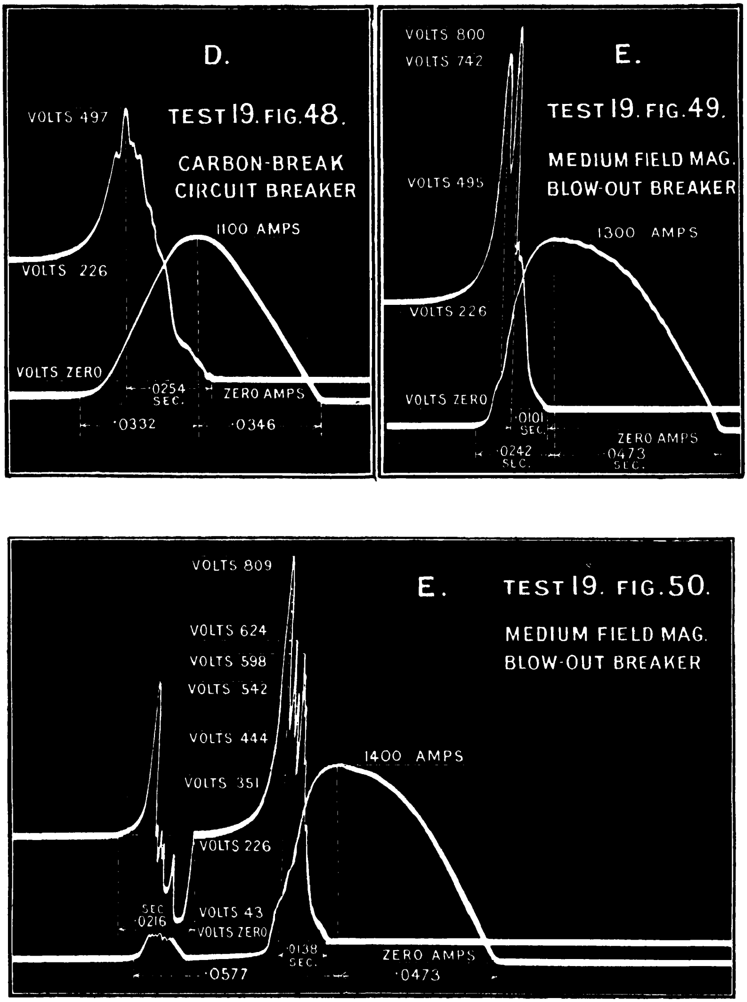


Test 19.—Fig. 75g. Test on D.C. Breakers.

an automatic breaker. Difficulties are encountered in the conduction of the hot gases formed on rupture due to the confined area of the explosion in the case of the enclosed fuse; the open type fuse admits of easy expansion, the conducting stratum travelling from point to point. The

equation given in *Watson's Physics* on the transference of heat may be used hypothetically—

$$Q = \frac{K\,A\,(T_2 - T_1)\,t}{d}$$



TEST 19.—FIGS. 75 H, J, and K. Test on D.C. Breakers.

Q = The quantity of heat in calories.

K = Constant independent of area temperature, but changes with substance used.

d = Distance of transmission of heat.

t = Time in seconds in which a given number of heat units would pass from one surface to the other.

$T_1\ T_2$ = Temperature of the fuse casing at the surface and the temperature of the fuse link, respectively.

A = The cross sectional area of the link.

Transposing this equation we get—

$$\frac{Q}{t} = \frac{KA\,(T_2 - T_1)}{d}$$

and representing calories we get Q/T by Q^1 = again

$$Q^1 = \frac{K\ A\ (T_2 - T_1)}{d}$$

One calorie per second = $4{\cdot}189 \times 10^7$ ergs per second.
10^7 ergs per second = 1 watt.
one calorie per second =4·139 watts.

We therefore get by the equation—

$$Q^1 = \frac{I^2R}{4{\cdot}189}$$

I^2R = watts loss in fuse

$$I = 2{\cdot}045\sqrt{A\,\frac{(T_2 - T_1)}{d}}$$

As K is a constant, we apply this also to the equation —

$$I = 2{\cdot}045\ K\sqrt{A\,\frac{(T_2 - T_1)}{d}}$$

Applying these equations to an enclosed fuse it will be seen that by the breaking or opening of a short circuit, or even on a predetermined setting, a substantial amount of energy is absorbed or converted in comparison with the open-type fuse and a much longer time elapses, practically double, in the discharge of the vaporized "ions" and their condensation.

Thus the multiple fuse link, or several strips of fuses in parallel, are used in order to effect the rupture under different conditions. Thus with a single strand of fuse the condensation is not sufficiently rapid to prevent the pressure reaching a straining point bursting the holder. With the stranded link or links in parallel the cooling is more rapid and the explosion pressure in consequence is not so great. The time element is changed, but the ratio of condensation to that of the single strand is practically doubled. It might be remembered that in a paper the author presented to the South Wales Institute of Engineers (vols. xxvii. 4, 5), 1911, it was proved by an oscillograph record that the potential of a circuit was not materially disturbed in comparison with potentials arising from the opening of circuit breakers. The induced E.M.F. did not rise materially above that of the normal circuit voltage, and also the induced rises of potential due to the use of the multiple fuse link affected the potential to the extent of about 35 per cent. above that of the single fuse link. This appears extraordinary, seeing that the phenomena of the induced rises are dependant upon the rapidity of opening of the circuit $\frac{d^1}{dt}$. This equation is affected, however, by external influences which ensure the rupturing effect taking place before the E.M.F. assumes such a high value. When applying the fuse oscillograph records illustrated in this book, some discrimination is needed, as the calorific value is such an inconstant quantity and the constants of the metal so variable that it is impossible to get definite results of a comparative character. Attention is therefore directed to particular tests rather than to comparisons of a series. The value of such tests consists in the record of current and voltage rises with time element and the energy absorbed. A test on a six-strand 100 ampere fuse opening in 0·03 of a second showed an increase over the single strand of 80 per cent. watts input, or in

another case recorded, the watt second input in a fuse was 23,000 watt-seconds against that of a similar single-strand fuse of 44,000 watt-seconds. Practically double the energy is absorbed by the rupture of a single link combination. In many cases the enclosed fuse of the cartridge type with a single fuse strip has been objected to, as the maximum disturbance in these cases shows on test about 20 per cent. more than in the case of the multiple fuse, since the greater the current the more violent is the internal pressure, bearing in mind at the same time the condition of the disintegration or vaporization of external "ions." The tests on a 3,000 ampere 500 volt enclosed fuse of the porcelain type indicated small inductive rise, and although of the multiple link form fitted with gas ducts the explosions were terrific. The test on the single link exactly similar burst the holder to atoms, the current rush being 150 per cent. greater before bursting. In another test the energy absorbed was four times greater on the single link than on the multiple link on an artificial short on a 10,000 battery fused at 4,000 amperes in two seconds. The expansion of a fuse element to its vaporized form is 2,000 times its normal. The presence of humid atmosphere or the presence of water in air which is expanded by heat of course accentuates the force of explosion, hence in some industries the provision of forces to counteract such expansion is of course necessary. The conversion of water into steam by an explosion is about 70 per cent., 30 per cent. being left in its natural state.

The understanding of the theoretical considerations is of great importance in the design of such gear, and while many engineers impose economical limits, the decline of design is of natural sequence. Hence we notice that the fuse has lost its position in the market, solely because the design has not presented its advantage, while in other countries fuses of 4,000 amperes capacity are made and installed with success, and have shown that such currents can be ruptured without such inconveniences as burst handles

and violent discharges. The chief difficulty with the fuse is its inconstant value when exposed to the atmosphere, and even assuming that the 100 or 300 amperes is quite satisfactory, then a 5,000 ampere fuse, if properly designed, could be equally as good and open the circuit in exactly the same ratio.

In many cases the middle of the fuse strip is of less section than the remainder, thus having a higher current density, and a bulb is provided which absorbs the heat less rapidly at that point, so that the explosion force acts outwardly in proportion to the current increment. In some high capacity fuses the fuse element is strained under mechanical tension, so that when the temperature rises the circuit is ruptured before its maximum explosive force is reached. Hard metals, owing to their high fusing points, are not so good as metals of low fusing temperatures. The important points with an enclosed fuse are—

(1) Conversion of heat.
(2) Concentration of explosive force.
(3) Quantity of stranded wires.
(4) Method of clamping.

contact faces, laminations are often provided either on this brush or fixed contact. These forms of contacts are self seating, and are much cleaner and possibly the best practice. It is not recommended that currents heavier than 700 amps. at 500 volts be broken by a quick break switch. Usually there is a circuit breaker in series with same which is tripped should the circuit require disconnecting. Fig. 76 illustrates a form of slow break switch. When dealing with heavy currents a switch of the form of Fig. 76 requires great mechanical effort for its operation. It is therefore very desirable that under these circumstances the switch should be designed with a toggle movement, reducing the mechanical energy necessary for operating the switch. Such a switch is illustrated in Fig. 77. This switch, however, is not designed to break under load.

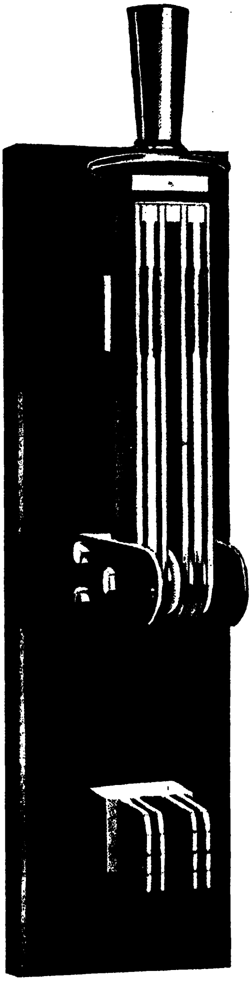


FIG. 76.—Illustration of Knife Switch.

Several improved features have been introduced of late in the design of air break switches, one of the most important being the straight through connector. In this form of switch the contact surface losses are reduced and also the soldered connexions hitherto met with in design. These features are negatived to a certain extent in that the action of the switch is not quite so good as that of its predecessor. When dealing with voltages higher than 600, switches of the standard design for D.C. work, as mentioned

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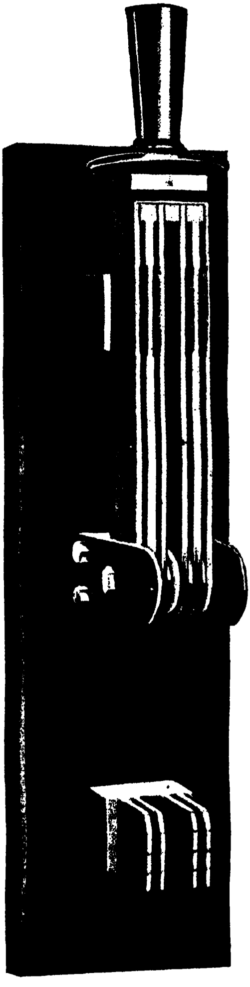

FIG. 76.—Illustration of Knife Switch.

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above, undergo different treatment. A switch lately designed by the author for 2,000 volts D.C. has a series of breaks in parallel with the main contact, so that when the main switch contacts separate, the arc is dissipated over 8 spark gaps. These switches replaced the horn

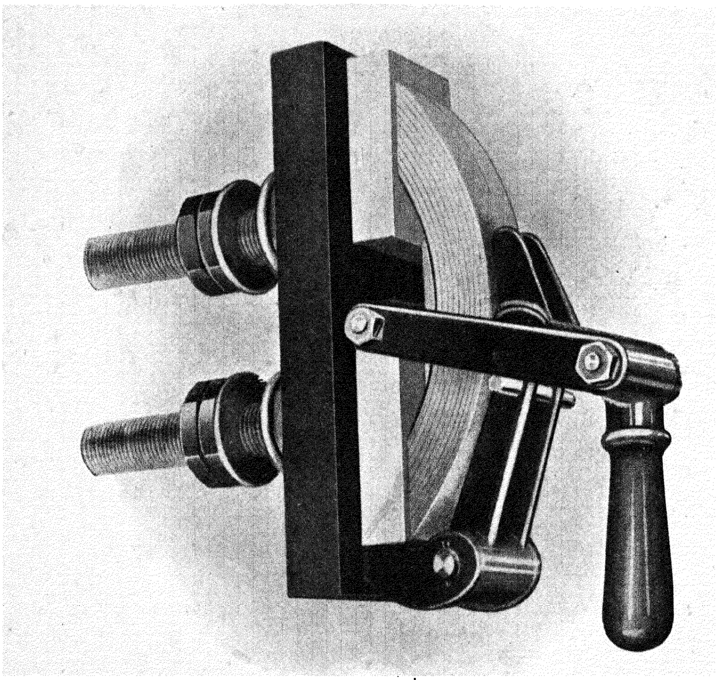

FIG. 77.—Laminated Contact Switch.

form of switch used on the Continent, and were quite effective if protected from dust and atmospheric conditions. The horn form of D.C. switch designed for a minimum break across the horns of 0·12 inch for 500 volts pro rata, caused considerable trouble on the service mains. It might be mentioned that the arc contacts of the first-named switch

were made of easily oxidizable metal, so that by the action of the arc they are covered with a non-conducting oxide which in operation is removed by friction. It is not considered good practice on high D.C. voltages to depend upon

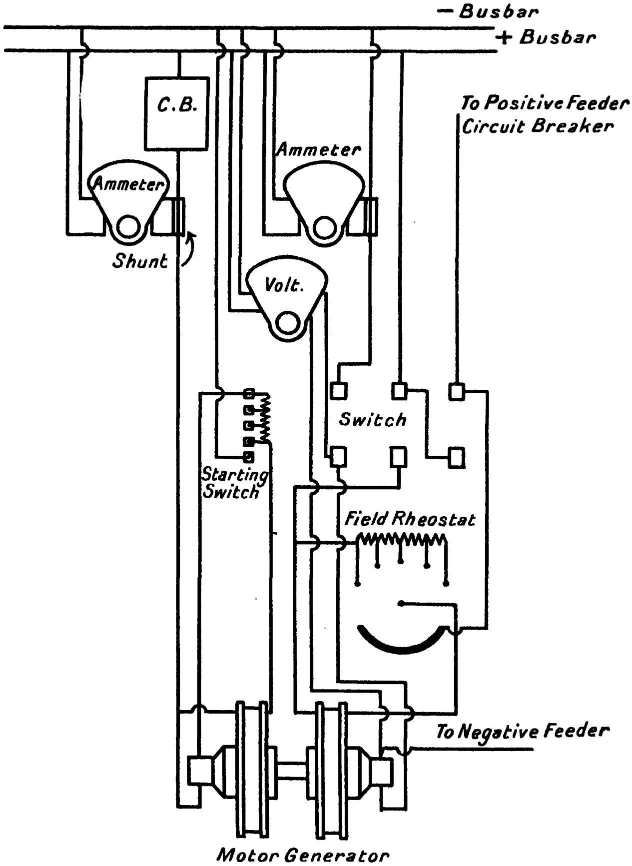

FIG. 78.—Diagram of Motor Generator Panel.

the electrodynamic action of the current. The following series of diagrams show some of the standard methods of connexions.

Motor Generator Panel.—Fig. 78 illustrates connexions

for a motor generator panel for negative booster in D.C. traction circuits. Amplification of the diagram is unnecessary with the exception that additional gear can be provided with interlocking. According to general practice the diagram will serve as a standard equipment.

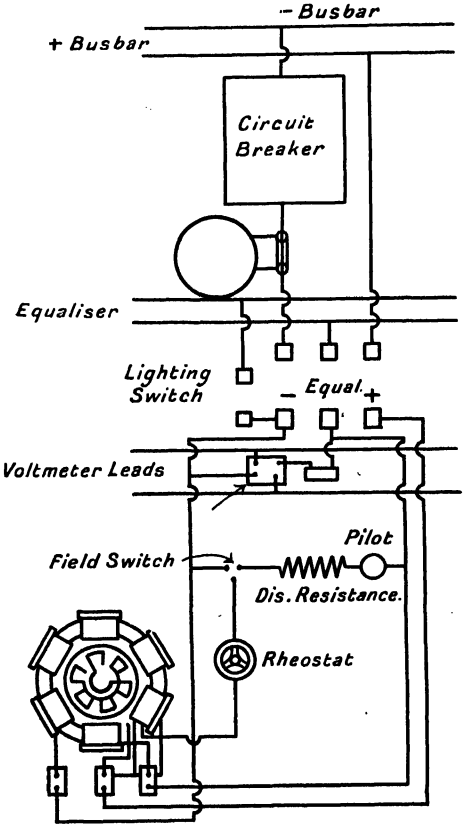

FIG. 79.—Diagram of Generator Panel.

Generator Panels.—Fig. 79 is a diagrammatic arrangement of a compound wound generator which was fully discussed previously. It will be noticed that only one circuit breaker is shown, and automatic protection between the equalizer and series winding is not included, such diagrams

only being intended as a basis upon which to consider the nature of the gear to be installed.

B.O.T. Panel.—Fig. 80 is a diagrammatic arrangement of a standard Board of Trade panel of the three voltmeter type

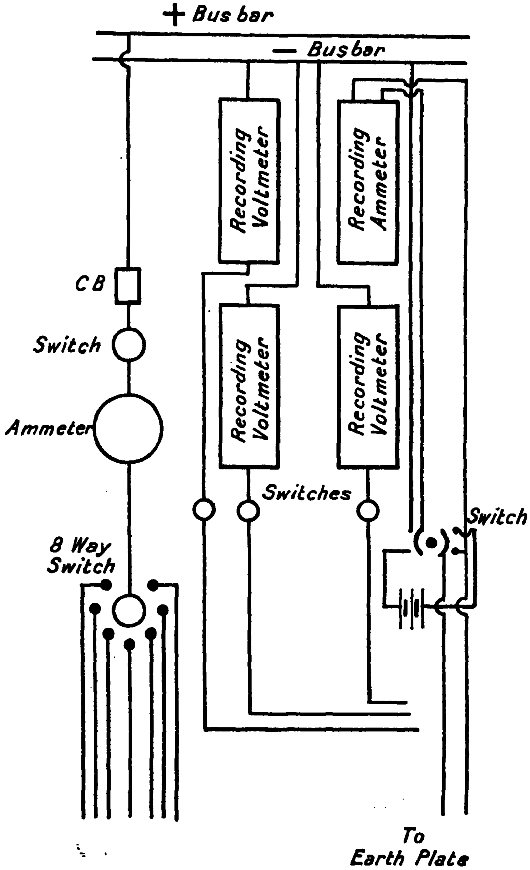

FIG. 80.—Diagram of B.O.T. Panel.

for traction circuits. The general design of this panel has not been subject to modification as in other panels, and has remained standard for a number of years, chiefly because its main features are those of measurement.

Traction Feeder Panels.—Fig. 81 shows a simple form of traction feeder panel for a single continuous current circuit. This form of panel, like the B.O.T. panel, has under-

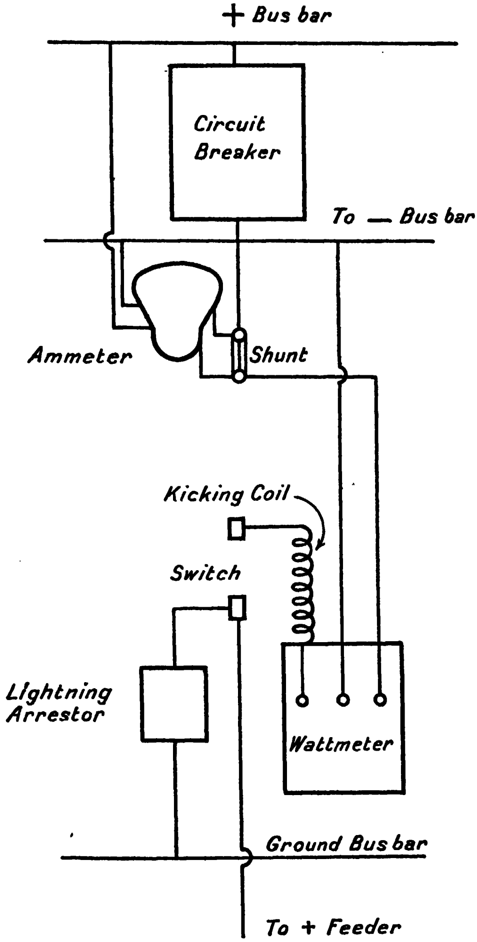

Fig. 81.—Diagram of Traction Panel.

gone very little change in design, and is consistent with modern practice.

Three-Wire Balancer Equipment.—Fig. 82 shows one of the three-wire balancer equipments. In this connexion

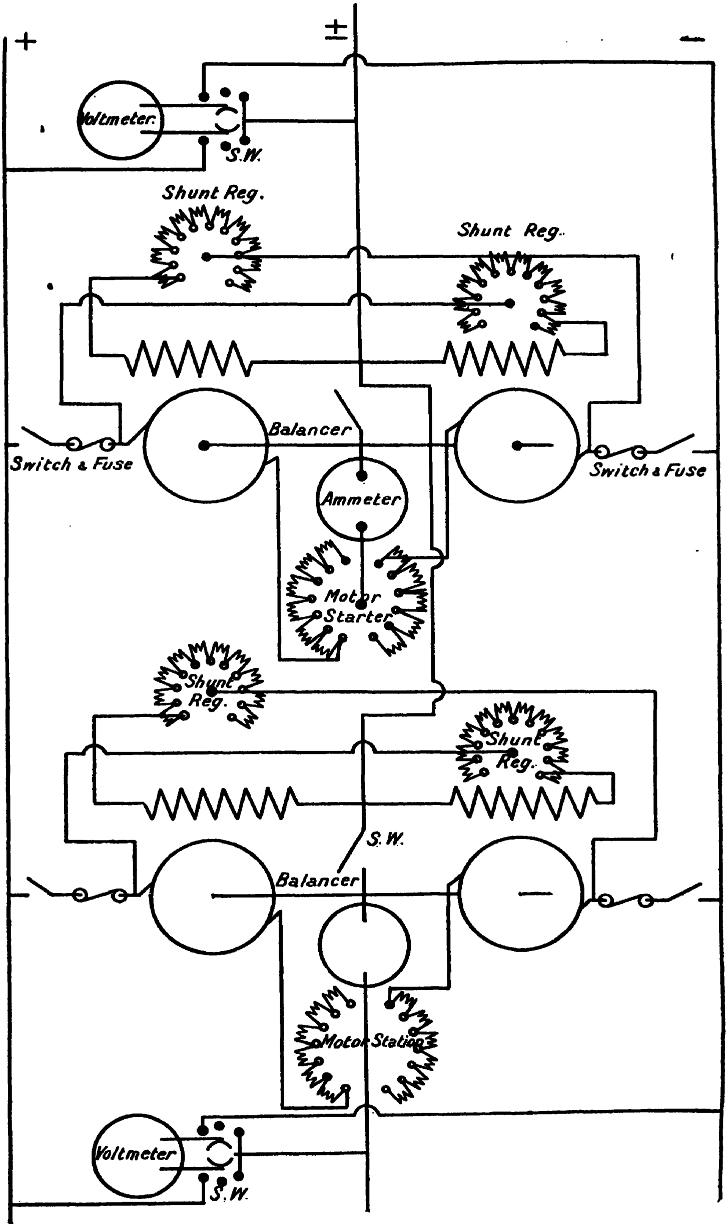

FIG. 82.—Diagram of Balanced Equipment.

it may be stated that the design varies considerably according to the plant to be protected. The absence of automatic gear and interlocking is particularly noticeable. There

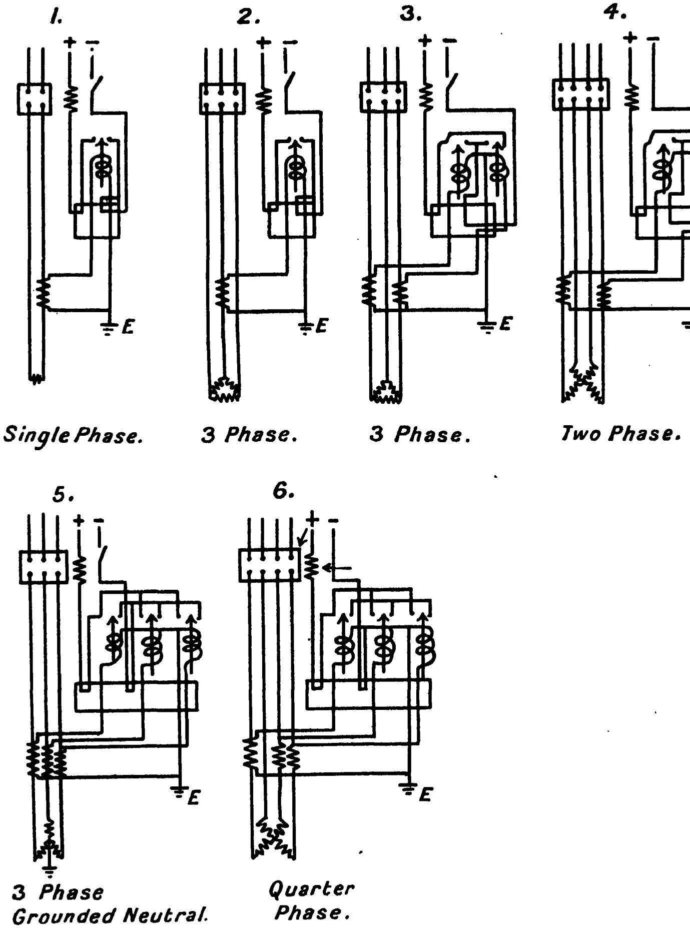

FIG. 83.—Six Diagrams of A.C. Circuits.

are so many questions arising out of the form of balancing that a standard scheme cannot be suggested. The diagram however will represent the general application of such work.

Alternating Current Panels.—Fig. 83 illustrates a

series of standard diagrams 1 to 6 for single phase, two phase, three phase interconnected, and grounded neutral. These diagrams only represent the main connexions and protections. Measuring instruments and other refinements may be added as may be desired. As shown in diagram the low tension connexions introduce a terminal board;

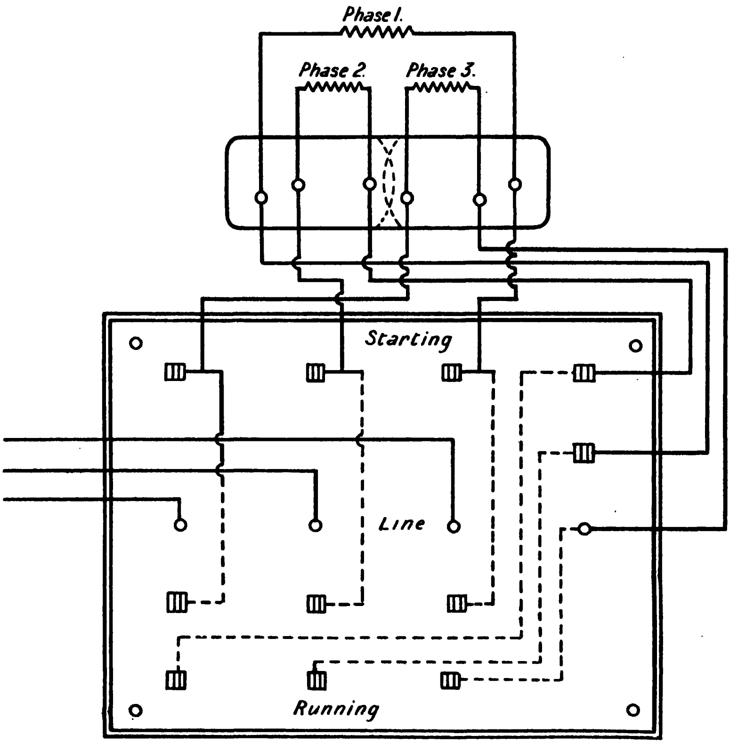

FIG. 84.—Diagram of Starting Switch for Induction Motor.

although omitted in many cases in switchboard design this feature is a very desirable acquisition.

Starting Switch for Induction Motors.—Fig. 84 is a diagram of a starting switch for 3-phase induction motors. The dotted lines are connexions made at the back of the panel. There are many objections to this form of switch,

particularly in reference to the absence of fool-proof measures. It will be seen that an operator can switch over to the running position before putting the switch into starting position. The switch should be made to include three positions if automatic. 1st, starting position; 2nd, running position; 3rd, overload position. The rotary form of switch lends itself conveniently to such an arrangement. The final position is the adjustment of the overload setting, which automatically opens the circuit at a predetermined value. In starting up such a motor a considerable current, exceeding that of its normal overload rating, even as much as five times its normal rating, is set up when under acceleration of speed; hence, unless some means are provided whereby the trip coils are set up to this current increment, the circuit, if the switch be of the free handle type, could not be closed.

CHAPTER VII

MERCURY ARC RECTIFIER—PRESSURE OF GASES—EXPLOSION-PROOF GEAR—GAS TIGHT GEAR—COLLIERY CONDITIONS—STATIC BALANCERS—EARTH DETECTORS—CONTROLLERS—SERIES CONTROL—SHUNT COMPOUND CONTROL DESIGN—GENERAL PRINCIPLES—FACE PLATE STARTERS—RESISTANCES—SOLENOID BRAKE—RHEOSTATIC BRAKE—CRANE CONTROL—CALCULATION OF RESISTANCES—CURRENT INCREMENT—TABLES—B.O.T. REGULATIONS.

Switches for Mining Work.—As referred to previously in the book, ordinary iron-clad air break switches are not gas tight, even though the joints be lined with rubber and sealed, as external gases such as are found in fiery mines penetrate through the small orifices of the case. Hence, a switch on rupture is liable to cause an explosion, affecting the surrounding atmosphere. To minimize these risks the most advanced design of air break iron-clad switch has wide flange joints with metal face to face contacts, so that on the rupture of a circuit the pressure and the gases formed do not affect the external atmosphere. As, however, the force and results of the explosion are in proportion to the volume and densities of the gases, together with the relationship of contact to cooling area, one design will not necessarily meet all the varied conditions of service, which service is generally determined by the density of the gas exposed, the pressure of which under explosion may vary in the case of fiery mines up to ten atmospheres. It is very evident, then, that a switch must be of such design that whatever conditions are met with in service, the exposed gases cannot penetrate to the

inner portion of the switch, and also the switch under consideration must be so constructed that it is necessary to remove the explosive gases before the switch can be put to service. Under these circumstances oil switches appear to be the only satisfactory solution to the problem. If, however, the capacity of the circuit is large and oil switches inconvenient, then the following chief factors in design are essential :—

(1) That the switch must be explosion proof.

(2) That it must be interlocked so that the switch must open before the case, and the case must be closed and sealed before the circuit is made alive.

(3) That it must be gas tight.

(4) That there are no exposed connexions.

(5) That the arc must not affect external atmospheres.

(6) That its insulation must be not less than 5 megohms between poles and earth with circuit closed.

On the Continent the switch chamber has been filled with a heavier gas which excludes lighter gases external to the case; this gas is equivalent to carbon dioxide CO^2 of a specific gravity of 1·529, that of air being 1. There is a tendency to supply switches of this character if oil switches cannot be used under fiery conditions.

Static Transformer Balancer. Fig. 85 illustrates the form of connexions using static transformers to balance feeders at sub-stations without the use of rotaries. If the sub-station is supplied with D.C. current from main station it can be balanced by the common balancer in the main station, or a separate balancer can be run from busbars A and B. In the event of sub-stations being supplied from rotary converters, the system can be balanced by tappings taken from the low tension side of static transformers supplying current to the rotary converters. The main D.P. switch is so arranged that current is not broken in changing over, and enables the middle wire bars to be supplied from the main station balancer or from the static

transformer. To balance feeders from transformer, close F1 or F2, according to the requirements of load, with B2 switch in on position. To balance from main station,

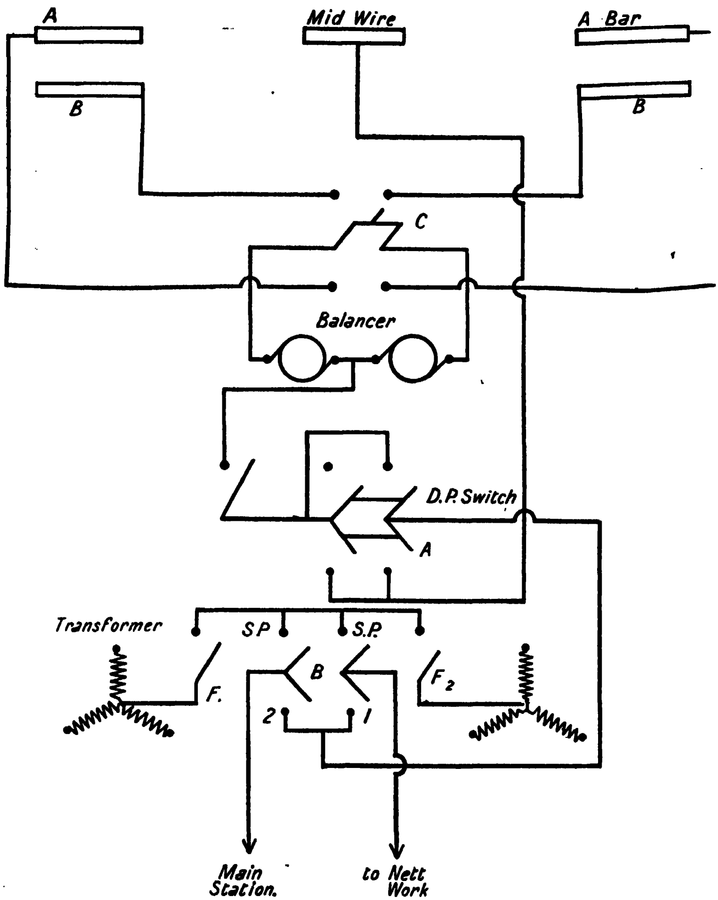

FIG. 85.—Diagram of Static Balancer Equipment.

switch B1 in bottom contacts and switch A in top contacts, switch C in bottom contacts. A study of the diagram will show many refinements in the connexions; in addition it is impossible to switch on a short. This system is in

use in a large electric supply undertaking, and is working very successfully.

Booster Panels.—Fig. 86 illustrates a standard form of connexions for Booster control. Fuses are shown on the diagram, but these can be replaced by circuit breakers with or without time limit. A considerable reduction can be made in the number of switches for this control.

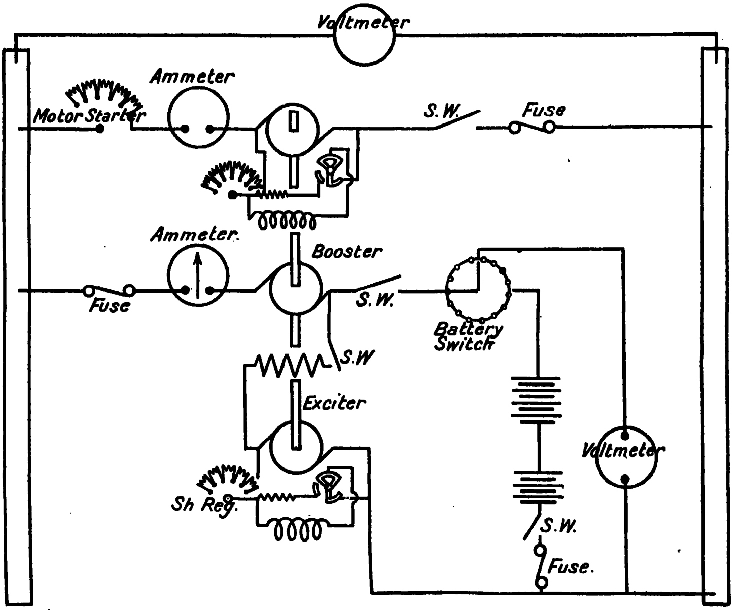

FIG. 86.—Diagram of Booster Panel.

This diagram, however, represents the connexions used on some of the Swedish stations where D.C. is employed.

Earth Detectors.—Figs. 87 and 88 illustrate a scheme of earth detector for three-phase three-wire system with neutral earthed at station and for direct current. In the previous chapters of this book it will be seen that on colliery work, the provision of such device is essential, and without it a switchboard would not conform to H.M. rules and regulations. In the case of Fig. 88 the device as shown

will not indicate an earth separately on each phase, but will indicate an earth on either of the three phases. This in some instances would not be suitable as it is often necessary that each phase should register its own fault. If such is required, the three voltmeter method can be applied, or a shunted indicator, in the case of high potentials, connected in circuit. As stated before, the system should

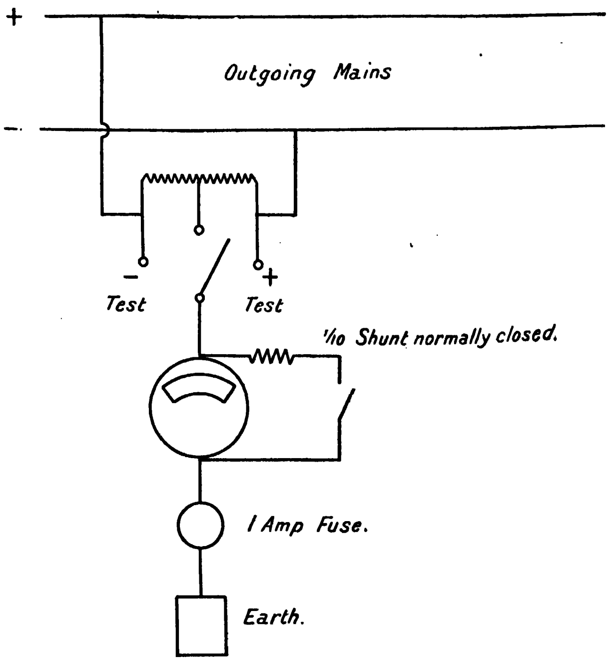

Fig. 87.—Diagram of Leakage Indicator D.C.

have automatic earth protection, whereby each circuit is relieved should the fault assume quantities exceeding those prescribed, in which case it would not be necessary to provide additional indicating instruments for the same purpose. Manufacturers provide a scaled diagram with such instruments from which calculations can be made relative to the value of earth current.

Controllers.—For heavy power work, and in cases where frequent stopping and starting is demanded, a controller is supplied. This gear is usually of the barrel form of design, and has great mechanical advantages over the "face plate starter." For crane work, it is a necessary part of the electrical equipment, and in the case

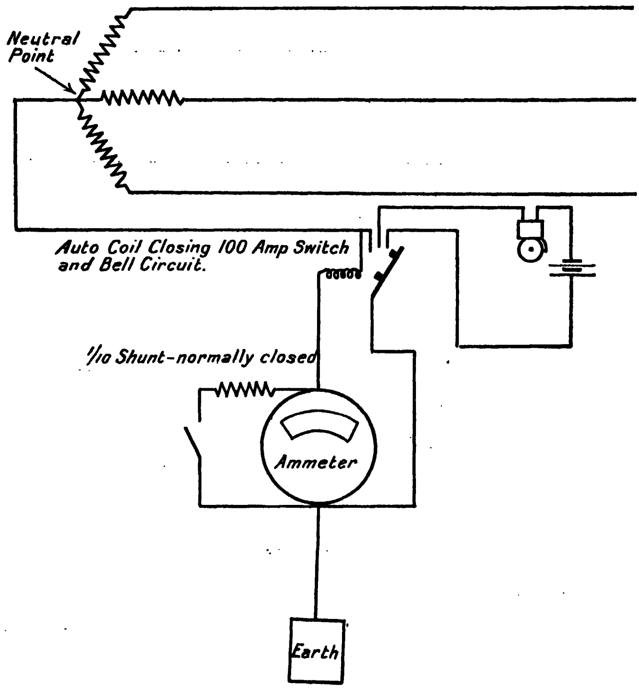

Fig. 88.—Diagram of Leakage Indicator 3 Phase.

of dockyard work, or similar electrical operations, the advantages of the controller form of regulation override those of the face plate starter. On the other hand, for light work and the usual application of motors, the face plate starter is indispensable. The barrel form of controller consists of a main drum, which is insulated from the spindle on which there are fixed contacts. Associated with

the main spindle there is a ratchet which has a definite position on each contact point. As the controller is operated, the fixed contacts form connexions to cable leading contacts, having between them arc shields, and over which there is a magnetic blow-out. By this means the circuit is formed and steps of resistance cut-out until the motor comes up to speed. Fig. 89 is a diagram of a series type of controller used extensively for crane duties. The blow-out

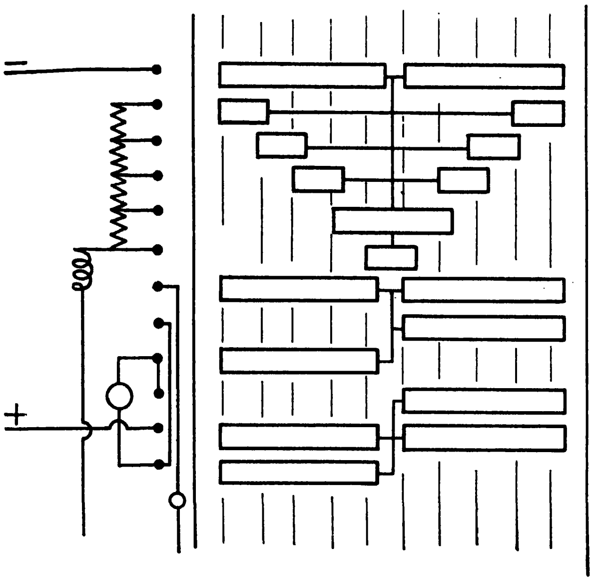

FIG. 89.—Diagram of Reversible Controllers.

coil is wound on a wrought-iron core and is in series with the line. One of the most popular constructions of magnetic blow-outs is the swing-back blo-wout. In this case the blow-out coil is wound as before with wrought-iron arms on which are mounted the arc shields, and fitted to the case by a hinge joint. The convenience of this arrangement is that the blow-out arm can be opened to admit inspection of the contacts. It is advised that the insulation be-

tween the barrel and the spindles should be of mica; sulphur compounds, etc., are not good practice.

Fig. 90 (diagrams 1, 2, 3, 4) illustrates the connexions

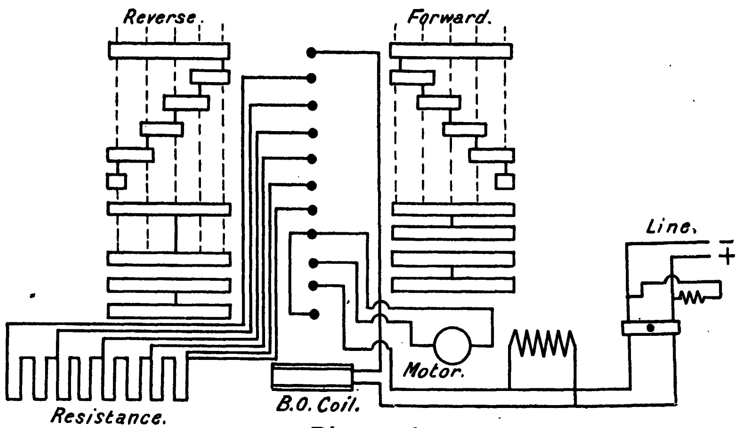

Diagram 1.

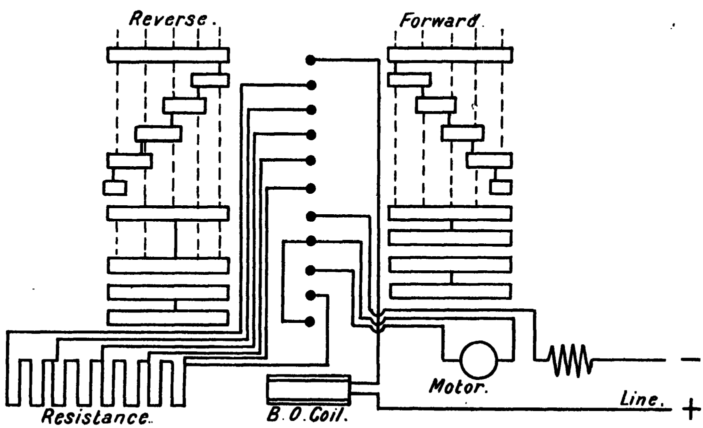

Diagram 2.

FIG. 90.—Diagrams of Reversible Controllers.

used for series motor wired single pole, series motor wired double pole, and also for controlling shunt, and compound wound motors. The single pole wiring is used where there are several motors having a common return wire,

double pole wiring being used in connexion with isolated motors. These controllers may be used for other special purposes. In hoisting and lowering on travelling cranes

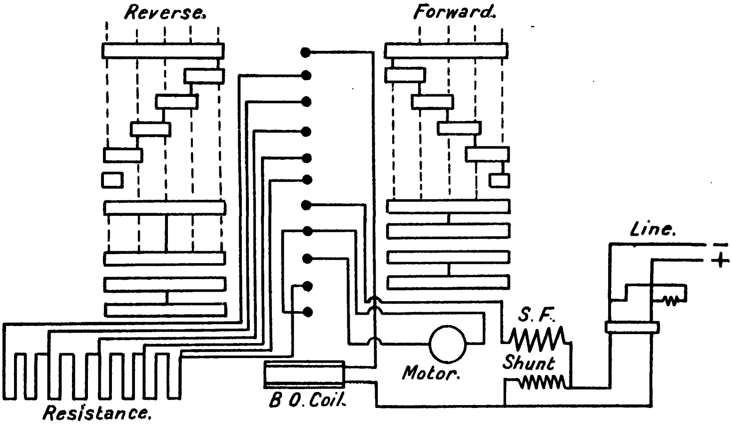

Diagram 3.

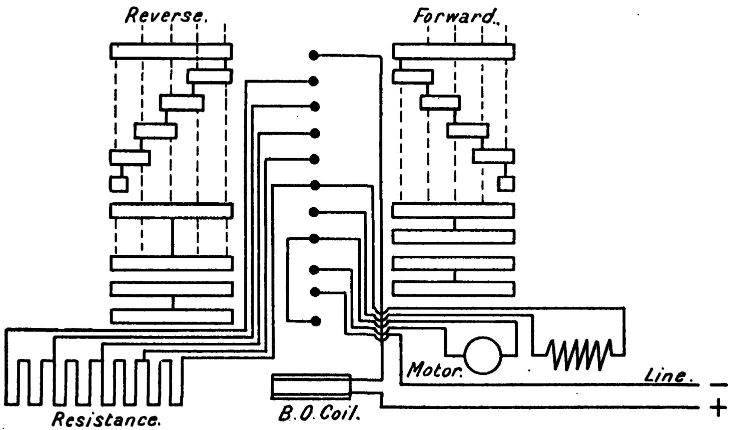

Diagram 4.

FIG. 90 (continued).

it is often necessary when lowering loads to brake the speed of the motor, either by solenoid or rheostatically. Fig. 91 shows a diagram of a reversible series controller with two brake positions in either direction, and Fig. 92 a similar

diagram having eight lowering positions and six hoisting. Manufacturers' standards vary as regards the number of

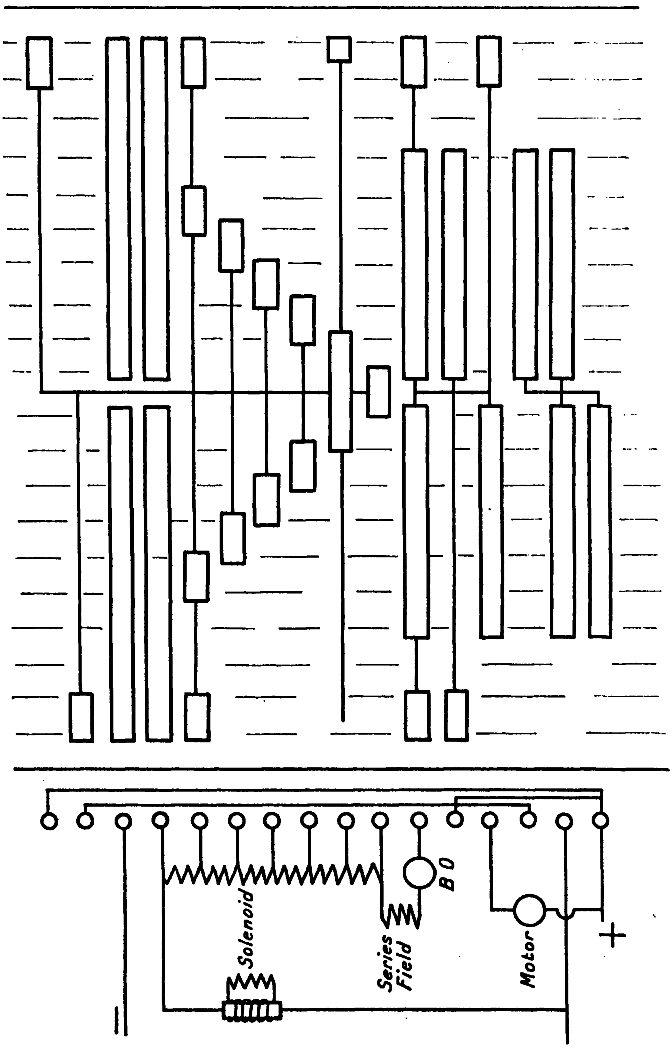

FIG. 91.—Diagram of Reversible Controller with Solenoid Brake.

positions for each size of motor. Usually for a 10 H.P. motor the resistance is cut out in five steps; for a 15 H.P.

motor seven steps, and so on according to the size of motor governed. Fig. 93 is of a controller (reversible) used in

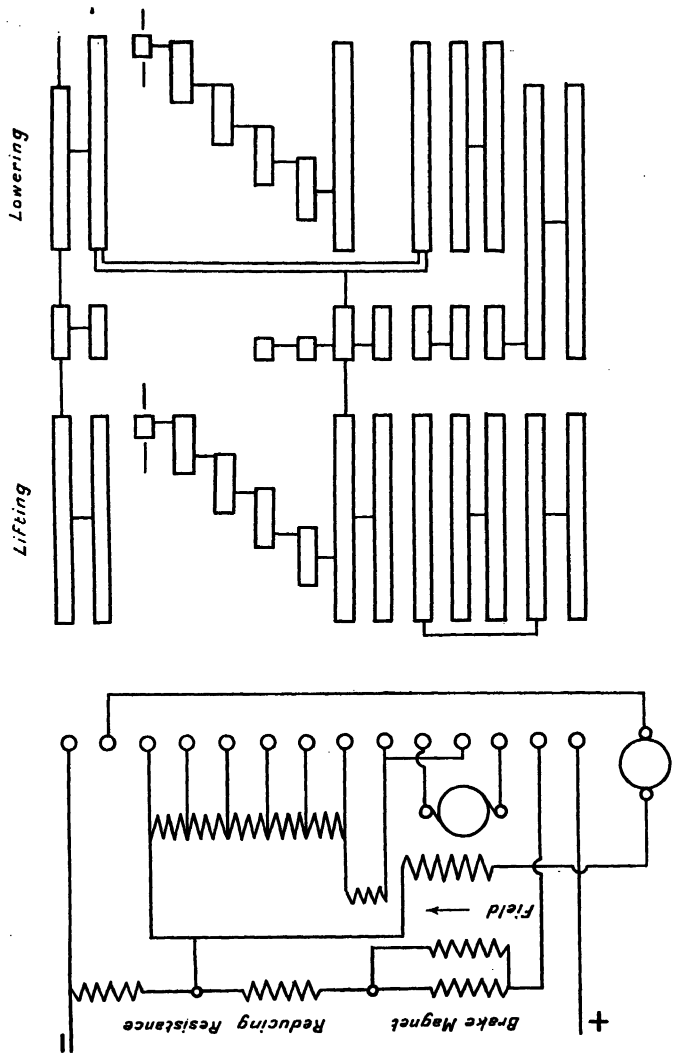

FIG. 92.—Diagram of Reversible Controller with Magnetic Brake.

connexion with a three-phase induction motor. The same general construction is used. Magnetic blow-out is not

supplied as in the case of a D.C. series wound controller. The face plate starter needs very little discussion as to its mechanical features, as all these are well known and of standard practice. The electrical features and data, however, are given below.

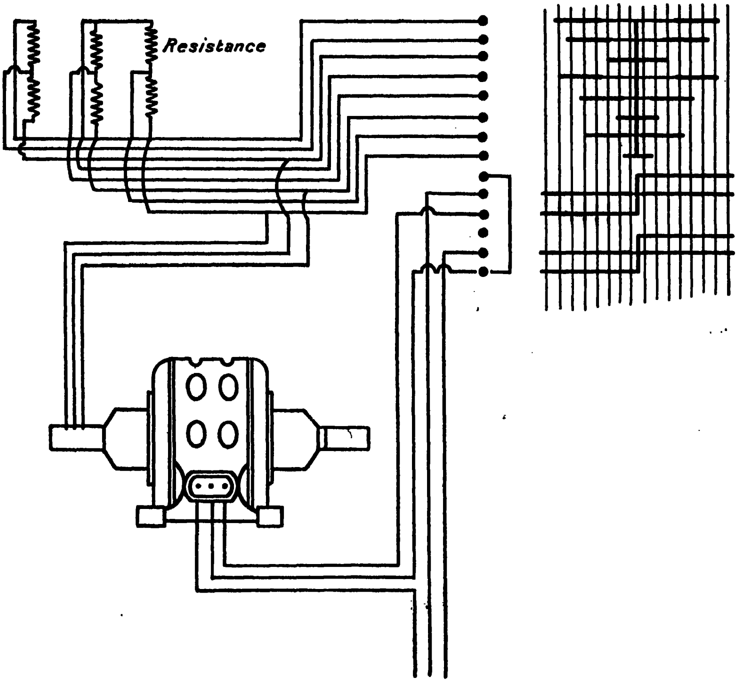

FIG. 93.—Diagram of Reversible Controller 3 Phase.

Calculation of Resistances.—Shunt wound starter. Starting current C^1 is a little heavier than the normal current of the motor, assuming there is no back E.M.F. at starting-point. The equation is—

$$C^1 = \frac{E}{R + r^a}$$

The figure R is the total resistance of the starter and r^a the resistance of the armature. On first contact when the armature reaches its normal speed, at this point, the

current then is normal, a back E.M.F. is produced $= E^b$ proportional to its low speed, the equation is—

$$C = \frac{E - E^B}{R + r^a}$$

The next contact produces a little finer position, but as the resistance is diminished, the current has increased. There is naturally an oscillation of current in moving the contact arm, but which becomes normal on its position in the same ratio as the back E.M.F. of the armature increases, the equation for the next contact is—

$$C^1 = \frac{E - E^B}{R - r^1 + r^2}$$

As the number of contacts are made, so the equation is extended during the whole circuit. The peak of the current rush at the time of switching should not exceed the starting current. The question of steps is determined by the rate of acceleration, and the current rush by switching, equation; N = steps.

$$N = \frac{\log\left(\dfrac{\frac{E}{C^1}}{r^a}\right)}{\log\left(\dfrac{C^1}{C}\right)}$$

The above equation holds good for series motors of a constant torque with constant current. For motors working on an inconstant load the calculation is now modified to suit requirements and extended as the case may be. A starter designed to start a motor at no load, is again a different problem as the starting current is about 20 per cent. of normal, and is so small there is no perceptible armature reaction or voltage drop. For motors starting up on heavy duty, say up to 100 per cent. of normal current, the controller type of starter is used with resistances graded accordingly.

Table of amperes per phase at unity power factor is appended.

TABLE OF AMPERES PER PHASE.

THREE-PHASE.

K.W.	Volts.										
	1,000	1,200	2,000	2,300	2,500	3,000	4,400	5,000	5,500	6,000	6,600
100	57·8	48·2	28·3	25·2	23·2	19·3	13·1	11·5	10·5	9·6	8·77
110	63·5	52·9	31·7	27·6	25·4	21·2	14·3	12·7	11·5	10·6	9·62
120	69·3	57·8	34·6	30·2	27·7	23·1	15·7	13·8	12·6	11·5	10·5
130	75·1	62·6	37·5	32·7	30·1	25	17·1	15·0	13·6	12·5	11·4
140	80·9	67·5	40·4	35·2	32·3	26·9	18·4	16·2	14·7	13·5	12·5
150	86·7	72·3	43·3	37·7	34·7	28·9	19·7	17·3	15·8	14·4	13·1
160	92·4	77·1	46·2	40·2	37·0	30·8	21	18·5	16·8	15·4	14
180	104	86·7	52	45·2	41·6	34·6	23·6	20·8	18·9	17·3	15·8
200	115	96·3	57·7	50·3	46·2	38·5	26·2	23·1	21	19·3	17·4
225	130	108	64·8	56·6	52	43·3	29·5	26	23·7	21·6	19·7
250	144	120	72·1	62·8	57·7	48·1	32·7	28·8	26·21	24	21·8
275	159	132	79·4	69·2	63·6	52·9	36·2	31·8	28·9	26·5	23·9
300	173	144	86·6	75·3	69·2	57·7	39·3	34·6	31·5	28·81	26·2
350	202	168	101	87·7	80·6	67·3	45·8	40·4	36·7	33·7	30·6
400	231	193	115	101	92·3	77	52·4	46·2	42	38·5	35
450	260	217	130	113	104	86·6	59	52	47·2	43·3	39·3
500	289	241	144	126	116	96·2	65·6	57·8	52·5	48·1	43·8
550	317	265	159	138	127	105·8	72·2	63·5	57·8	52·9	48·2
600	346	289	173	150	138	115·5	78·8	69·3	63	57·7	52·4
650	375	313	187	163	150	125	85·2	75	68·2	62·5	56·8
700	404	337	202	176	162	135	91·8	80·8	73·5	67·3	61·2
750	433	361	216	188	173	144·3	98·4	86·6	79	72·2	65·6
800	462	385	231	201	185	154	105	92·4	84	77	70
850	491	409	245	213	196	167	112	98·2	89·3	81·8	74·4
900	519	433	259	226	208	173	118	104	94·3	86·6	78·6
950	548	457	274	238	219	183	124	109	99·7	91·4	83
K.W.	1,000	1,200	2,000	2,300	2,500	3,000	4,400	5,000	5,500	6,000	6,600

Power Factor 1

CHAPTER VIII

THEORY OF SELF-INDUCTION—POWER FACTOR INTRODUCTIONS—STORAGE BATTERIES—THREE-WIRE DIRECT CURRENT GENERATORS—ROTARY CONNECTORS—MOTOR BRAKING—EDDY CURRENT BRAKE—RHEOSTATIC CONTROL—THREE-PHASE TRANSFORMATION—FAULTS IN INSTRUMENTS—GRAPHICAL PRESENTATION OF POWER FACTOR—SYNCHRONOUS MOTOR INTRODUCTIONS—B.O.T. REGULATIONS—CONCLUSION.

Self-Induction.—When a current flowing through a conductor is of constant steady value, the field due to it is an unvarying quantity. This field consists of circular lines of force which expand proportionately to the current flowing from the source of power; with increase of power the field becomes greater and with reduction the field collapses, cutting the current transversely, and finally disappearing altogether. A certain amount of time elapses before such changes take place. From the universal law the self-induced E.M.F. opposes the change in the current, so that we see in the preceding chapters that the current does not rise instantaneously to its full value as represented by Ohm's laws $C = \frac{E}{R}$, since the moment when current starts to flow there is an opposing E.M.F. generated which, together with the resistance, determines the value of the current at any instant under a given pressure. The changes are symbolized by $\frac{di}{dt}$, the E.M.F. of self-induction being represented by $E = -L\frac{di}{dt}$, the minus sign representing the

increase of current which is negative to the origin. Take, for example, a solenoid. If the lines of induction pass through the centre of same irrespective of leakage, and assuming 100 lines pass through 4 turns and 50 pass through 2 turns, we get $(4 \times 100) + (50 \times 2) = 500$ linkages. If the current is withdrawn the lines on the other loops will vanish by contraction, and affect the number of lines on the inner loops. Consequently, the effect of change must depend on the number of turns or loops in the solenoid. Thus if L represents the number of linkages or lines of induction when unit current is flowing, the inductance of the solenoid will be $L = \frac{L}{C}$, the E.M.F. of self-induction being $-L\frac{di}{dt}$.

L represents the self-induction, its value being 10^9 times the absolute unit. The presence of iron, however, changes the condition, by introducing wide variations of field, and graphical results of such effects are to be found in books devoted to the subject. Therefore the term inductance admits of very wide definitions, and is not to be considered solely as the ratio between the E.M.F. of self-induction and its current value at that instant. An increase of current is opposed by the self-induced E.M.F. In addition there is an E.M.F. which, forming the current, is greater than the opposing E.M.F. This, again, introduces 3 E.M.F.'s (1) The impressed (2) self-induced E.M.F., (3) the resultant, which is proportional to (1) and (2) as $E_R = E^1 + E^2$, the algebraical sign depending upon the increase or decrease of current. At any instant the current is represented by $C = \frac{E}{R}$, assuming the current is constant in value, therefore $E^2 = 0$, so that $E_R = E^1$, from which $C = \frac{E^1}{R}$. The division of E.M.F.'s may be represented by the relation of a motor to its armature, the electrical energy being

E.C. watts. The impressed E.M.F. is divisible into two portions: the one equal to the E.M.F. which forces the current through the resistance R; equal to C.R., the other equal to the back E.M.F.($E.^1$), developed by the motor as—$E = C.R. + E^1$. The work done is similarly divisible into two portions, one corresponding to C^2R as heat, and the other corresponding to E^1C, which appears as mechanical effort in turning the motor against the resistance of the load. These are precisely the conditions of expenditure of energy when an impressed E.M.F. causes a current whose strength is varying to flow through a resistance R, divided into two portions, in one of which energy is being dissipated in the form of heat, the other representing the energy stored up in the magnetic field. If E_1, E_2 and C be the values at any instant of the impressed E.M.F., self-induced E.M.F. and actual current flowing respectively, the one portion is equal to C^2R, the other E_1C; consequently when the field is being created we get—

$$CE_1 = C^2R + CE_2 \text{ as } E_1 = E + E_2$$

Thus energy is absorbed in the creation of a magnetic field, and it takes time to build up the field, but when once created energy is not being absorbed in its maintenance. Therefore, when judging the oscillograph records of the rupturing effects of circuit breakers on direct currents, the E.M.F.'s shown must be regarded in the same ratio. Also, the effects of the magnetic blow-out coil creating the artificial field referred to are instances of the values here recorded.

Power Factor Introductions.—In many instances rotary converters are used and result in modifyimg the power factor of a system. In some cases these machines may have no corrective value, and may introduce effective heating under load when operated at a power factor less than unity. It is only when rotary converters

are operated under these conditions that the leading wattless K.V.A. put into them would be of sufficient magnitude to bring about any appreciable improvement of power factor. For loads that are steady and well below the full load provision the rotary would have some corrective value upon power factor without heat troubles; but with a fluctuating load such as is found on railway work where compounding by reactance and series field action are common, the converter is under excited. A lagging power factor results under low loads. There is thus a definite heat effect on some of the coils which is and has been a source of trouble. Under conditions of unity power factor, the heating of each half of the phase is symmetrical, but when the power factor is lagging (when under excited) the distribution of heat is changed. That coil of a phase which is ahead with respect to rotation is heated very much more than any other coil. As the power factor decreases the heating increases, the equal heating of the rear coil diminishes while the region of least heating moves backward with respect to physical rotation from the centre coil toward the rear, so that when a certain lagging power factor is reached the coil least heated is actually the rear one. In the foregoing remarks it is understood that the rotary referred to is supplying direct currents, the alternating portion being run as a motor. At certain instants the current flows into the armature winding through the collector ring and commutator, and out through the direct current brush without commutation. In the coils adjacent to the collector ring the alternating current then flows in the same direction as direct current, while in the coils towards the middle of the phase the alternating current and the direct current are opposed. Although the condition changes from instant to instant, the net result for a complete cycle is a considerably greater current in the coils next to the alternating current terminals. Hence, assuming normal full load operation, neglecting losses, the heating

is variable at different points, and is generally greater at the ends than in the centre, the heating changes being much more rapid. It has been stated that the power factor of a circuit may be less than unity, due either to a load having capacity, or as leading current component. Also, that by supplying to the system additional current of opposite reactive characteristics to that causing reduction of power factor, the latter can be raised by an amount depending upon the relative magnitudes of the various components of the circuit. Thus a load with a low power factor due to inductive apparatus can be given a power factor approaching unity, either by adding sufficient non-inductive load, or more particularly by adding a load with capacity characteristics, thus introducing current with a compensating leading component. It is well to note that the operation of a rotary converter at 100 per cent. power factor introduces of itself a very considerable corrective effect by the addition of so many K.V.A. at the highest power factor to the system to be improved.

Storage Batteries.—The determining factors in the selection of storage batteries are (1) purpose, (2) size, (3) limits of current and voltage fluctuation, (4) cost, (5) hand or automatic control. One of the most original common systems is the operating of the two sections of the battery in parallel, the battery being connected in series for charging and in parallel for discharging. This is done in order to secure a sufficient voltage for charging without disturbing the line voltage or the voltage of the generators. Consider a battery for 110 volt circuit. The voltage of each cell at the end of discharge is 1·8 volts. Thus the number of cells required is $110 \div 1{\cdot}8 = 62$. The voltage, however, at the end of charge is $2{\cdot}6 \times 62 = 161$ volts, which is of course too high for the line voltage. With the battery divided into two halves in parallel we get 80·5 volts for charge, the excess volts being dissipated by the rheostat. In this connexion, to avoid losses by the introduction of the rheostat, the

battery may be divided into three parts, two of which are first charged in series for half the time necessary for a full charge, 2 and 3 are then charged in series in exactly the same manner, and finally sections 1 and 3. The voltage at the end of charge would be $2/3 \times 161 = 107$ volts. There is no limit to the various methods of charging, the above serving as an example. In many small installations where there is small demand for current, end cell switches are provided. The battery is charged with the circuits opened, direct from the generator, the voltage of same as in the case above being raised to 161 volts. The voltage of the cells during discharge is regulated by the end cell switch, by means of which more cells can be connected into circuit, as the voltage drops. These switches are used in many cases where charging is by a special machine called a "Booster." These switches can be made automatic by, say, the introduction of a relay operated by a voltmeter. Regulating switches of this character should be fitted with a double brush so wide that the battery will not be opened up during its movement from one contact to the other. In order to avoid the short circuiting of cells a resistance must be inserted between the main brush of the switch arm and the auxiliary brush, which will limit the short circuiting current to that of normal load. In cases where charging of the cells must take place during times of load, and where it is impossible to have the lighting switch open, a charge and discharge switch is provided. The voltage of the charge is regulated by the charge switch and the generator rheostat, while the discharge volts are maintained by the discharge switch, the cells being cut in or out to correspond to the line voltage. Batteries should be charged at their normal rate, generally eight hours, or as per directions on the accumulators, at a voltage of 2·25 volts per cell, the current being regulated according to the cell capacity. When charging a fully discharged battery it is well to start at 15 per cent. above normal rate until the volts

appear at 2·5 volts per cell. A gradual rise will be noticed up to say 2·45 volts per cell, after which the voltage will remain constant, as gases are being given off the positive and negative plates, which start about 2·3 volts per cell. The symptoms of full charge are the dark colour of the positive plates, the higher voltage, or even better, the specific gravity of each cell. It is important that the cells should not be overcharged. Rapid charging may be effected at twice the normal rate, and continued until the gas is relieved from the cell and the voltage constant at 2·6 volts per cell, at which point the electrolyte will have a milky appearance and be gassing freely. The temperature of the battery should not exceed 100° Fahr. Experience has shown that in charging and discharging, the best results are obtained when the temperature is between 70° and 90° Fahr. Lower temperatures will reduce the available capacity, which is regained under normal temperature. If the battery has its full rated capacity at 70° Fahr., it will have about 76 per cent. of its capacity at 30° Fahr., while at 90° Fahr. it will retain about 112 per cent. The electrolyte should be just below the level of the plates, and when fully charged, in the case of lead batteries, should have a specific gravity of 1,200 to 1,230. Should the specific gravity in some of the cells be lower than in others it is better to charge such cells separately at a low rate. If the cell regains its normal it has for some reason run down lower than its neighbours. If, however, the gravity does not come up or does not increase in temperature, additional acid should be placed in the cell. Internal short circuits are shown by failure of the voltage to rise on charge. These short circuits can be removed by passing a sheet of glass between the plates or removing the sediment. The questions of reverse polarity and the sulphation of plates are not covered by these comments, such points being outside the scope of control.

Three-Wire Direct Current Generators.—In many direct current installations three-wire distribution is adopted. In comparison with the two-wire system it will be found that for a given drop of potential, if the three-wire system be operated with a voltage between the outers and the neutral equal to that of the two-wire distribution, and if the neutral be the same size as the outers, a saving in copper of 62·5 per cent. may be effected. It may seem false economy to suggest that the neutral be of the same size as the outers, but it must be remembered that out of balance current and the effects of opening a circuit breaker cause the whole of the current to pass through the middle wire. In the early days of three-wire networks two separate generators were used in series with the neutral in common. Obviously this method was capable of improvement, as two machines were necessary though the load was small. This method was superseded by a balancer operating in conjunction with two-wire generators. This of course necessitated the continuous use of the set. The three-wire generator was designed to save the necessity of supplying and keeping on circuit the two sets of machines referred to above, with greater efficiency. The main features of the three-wire generator are practically identical with those of the two-wire; it is fitted with four slip rings which are connected to the armature winding in the same manner as a two-phase rotary converter. That is, taps are brought out at four electrically equi-distant points for each pair of poles and connected to the slip rings. From these rings wires are run to balance coils. These machines are designed to balance a 25 per cent. out of balance load, and to operate satisfactorily with 25 per cent. of the full load current of the generator flowing into the neutral wire with a voltage varying not more than 2 per cent. from normal. By the use of two balance coils the out of balance current is more evenly distributed in the armature winding. The balance coils consist of a single winding with a neutral tap brought

out from the middle point. The coil is wound on a laminated core of the shell type, and mounted in a case as a transformer. The field windings of all the north poles are connected in series and to one outer wire, and the south poles in series on the other outer wire to obtain a compounding effect from either side of the system when the load is unbalanced. Three-wire generators can be operated in parallel with each other or with two-wire machines. For this work the gear on the switchboard is very similar to that used on compound wound or parallel generators with slight additions and modifications. D.P. switches had to be supplied for each balance coil. Two D.P. switches replace the equalizer, and D.P. switch circuit breakers must be provided on each pole with the series field switch interlocked. Three-wire sets have a wide field of application, in that the advantage of the high voltage is retained in conjunction with current supply at low pressure.

Synchronous Motors in regard to Power Factor.—We have discussed the influence of rotary converters upon power factor, and it is proposed to outline the benefits of synchronous motors as regards the introduction of leading currents. Little attention has been directed to this in the past, as the operators in charge of induction motor plants were not acquainted with the provision of machines for that purpose. There is no doubt that the improvement of power factor is brought about successfully by this means, while on the other hand their introduction may not be good practice, careful discrimination being required. The power factor of induction motor installations usually varies between 55 and 80 per cent. Of course the lower power factor would represent under-loaded capacity, and this power factor could be improved by the use of smaller motors. In the case of arc lamps the power factor may be 70 per cent., and that for induction motors separately at full load, say 100 H.P. 80 to 90 per cent., half load, 60 to

80 per cent., while their combined power factor may be 70 per cent.

As an illustration, the effects of a synchronous motor on a circuit delivering 1,000 K.V.A. at 70 per cent. power

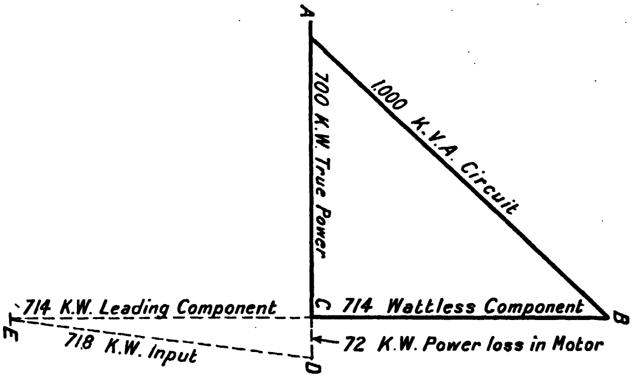

FIG 94.—Power Factor Diagram.

factor (700 K.W.), true energy will be considered. The 1,000 K.V.A. will be considered the full load rating of steam driven direct current generators, and it will be assumed that there is a demand for more power to the extent of 200 H.P. This may be done by raising the power factor of the present generating load, or by the addition of another set. Since the generators, as is often the case, are rated at 1,000 K.W. at 100 per cent. power factor, they only deliver 700 K.W. at 70 per cent. power factor. Therefore the available capacity of the generating set is 30 per cent. less vertical production. If the generators had a combined rating of 1,430 K.V.A. this plant would then deliver 1,000 K.W. true power. The illustration, Fig. 94, represents the 1,000 K.V.A. load A B; A C true power (700 K.W), and B C wattless component (714 K.W.). The angle B A C is the angle of lag, A C representing the direction of the voltage and A B the direction of the current, since there is $\sqrt{1{,}000^2 - 700^2} = 714$ K.W. wattless component

in the circuit lagging 90° behind the voltage. To raise same to 100 per cent. power factor it would be necessary to introduce an equal amount of leading wattless power into the same circuit. This is shown by the line C E, 180° from B C. Assuming the true watt loss in the motor as approximately 10 per cent. of its full load rating, and the drawing line C D 72 K.W. in phase with the true power of the circuit, the synchronous motor triangle C E D is formed in which E D 718 K.V.A. is the input of the synchronous motor, E C 714 K.W. its leading wattless component, and C D 72 K.W. its true power component. A synchronous motor, therefore, having a capacity of 718 K.V.A. floating on the circuit without doing mechanical work would raise the power factor of this circuit to unity, and reduce the load on this plant from 1,000 K.V.A. to 772 K.W. (700 + 72), or a reduction of 228 K.W. It will be seen that in case the synchronous motor is not made for mechanical power the capacity of the motor for obtaining unity power factor is quite large in comparison with the plant. The condition is changed if the synchronous motor has to give out mechanical energy in that a greater return is ensured by its adoption, the capacity of the motor being increased from 718 to 720 K.V.A., or by 2 K.V.A., it will deliver 21 K.W. mechanical energy in addition to raising the power factor to unity. By increasing its capacity to 830 K.V.A. or by 12 K.V.A. it will deliver 79 K.W. mechanical energy, or by increasing its capacity to 1,000 K.V.A. it will deliver 600 K.W. mechanical energy. Therefore 2 K.V.A. increase in capacity gives a return in mechanical effort of 1,050 per cent., 12 K.V.A. increase gives 658 per cent., and 282 K.V.A. increase gives 212 per cent. While it is uneconomical to raise the power factor to unity, it is or may be raised to 90 per cent., and can be graphically recorded as prescribed. An increase can be obtained when the initial power factor is low, at much less cost than when the power factor is high. Several instances and tests are recorded where, as above, by the use

of synchronous motors the power factor is improved up to 80, 90 and 95 per cent. While appreciating their advantages it may be false economy to instal synchronous motors on small installations rather than generators having a K.V.A. rating at a power factor likely to be obtained, and it is in default of a proper understanding of the effects of power factor that competition has covered up its technical points, since in some cases the difference between a rated output at unity or lower power factor is not realized. The more mechanical work the synchronous motor can do in addition to a leading current, the more efficient is the installation, noting that it rarely pays to raise the power factor higher than 90 to 95 per cent. Spare generators can be floated on the line to improve power factor, also rotary converters introduced at leading current.

Braking in Controllers.—In the preceding chapter descriptions and diagrams represent the application of controllers. On some work where lowering under load is at retarded speed, the controller has special points either for rheostatic effect or for the introduction of friction which prevents the speed becoming too high. To act as a brake the motor must not only absorb the energy of the moving parts, but it must exert additional torque to overcome the driving effects of the load. In the case of a lift, the dynamic brake must stop the armature and the load which tends to drive the motor as a generator. In the case of crane work the brake has to retard the torque, the speed being constant, as the energy in this case is less than if the load were stopped. This form of braking unless provision be made causes heat in the motor. In the case of a shunt motor lowering a lift, it is often running above its normal speed, delivering energy to the line exactly in the same way as an induction motor above synchronous speed. The eddy current form of brake often used now in testing is governed by the mechanical friction between the revolving and fixed parts. Both direct and alternating

current motors can exert a retarding effect by the reversal of current through the motor, and inserting sufficient resistance to reduce the torque of the motor to the desired amount, for instance, an induction motor with a wound secondary. By sending current through the primary of the motor so as to exert a torque opposed to the moving load and adjusting the resistance of the secondary circuit to control this torque a braking action is applied to the motor. So in the case of a direct current motor. By the application of direct current an alternating current motor can be retarded in the same manner in the primary winding. In the case of direct current motors dynamic braking consists in connecting the armature of the motor in a closed circuit with a resistance. This resistance may be used for acceleration or for heating as the case may be, in addition to its primary function. The motor used is necessarily increased in size owing to the heat limitations, and the potential of the machine must be kept within reasonable limits. Should the motor be running at a speed in excess of normal value with normal field strength, the voltage must necessarily be increased also. In stopping a direct current motor by means of this brake the active voltage of the armature is relied upon to cause the current to flow through the closed circuit. As the speed of the armature decreases the voltage also becomes less with less retarding torque. The use of a motor as a generator involves more complicated connexions, as is shown in the preceding chapter. There is no doubt that dynamic braking is the best form of retardation, as it involves practically no wear and tear as in the other forms of frictional resistance, as long as it is not abused. The control of the load is more positive, seeing that it depends upon the line voltage, which is rarely more than 5 per cent. out, whereas on the other hand the friction is dependant upon its absorption of heat which is not of a constant value, and is variable on the different steps of control. It is well to note the

practical limits of the various designs of motors for this work as set out in the following.

If the work required on the motor is small during braking, a compound wound motor may be used, the shunt field only being connected in circuit during braking action. If for heavy loads both shunt and compound windings must be used.

The controlling of the shunt field of a shunt wound motor by varying speed is advisable when the descending speed is in excess of hoisting speed, as the weakening of the field permits increase of speed without having the voltage of the armature exceed normal value.

In the case of series motors, where the load drives the motor, it is advisable to connect the series field as a shunt across the line during the first part of the braking operation, to make sure that the motor builds up as a series generator. In the diagrams in the preceding chapter the armature series field are in shunt together and in series with a limiting resistance across the line, so that sufficient torque can be exerted to start the load in a downward direction. It will be noticed that the motor is disconnected from the line, and a point may be made that the connexions between the series field and armature must not be broken.

Three-Phase Two-Phase Transformation.—In several installations in the country it is often found of value to transform from three to two phase currents. This can be done by using transformers, the primary of which is in the one case connected across the outer phases, the other across the inner and outer phase, the middle point of the transformer being interconnected, and the secondaries forming phase A and B as required. The E.M.F. induced in the transformer A will be equal to the E.M.F. impressed on the primary and in phase with it, while the E.M.F. in the secondary of transformer B will have the same value but will be displaced 90° in phase. Assume a non-inductive load on transformer B, and no load on A, a current will

flow in the secondary which will be balanced by a current 1·15 times that in the primary, since there are 86·6 per cent. of the total turns on circuit, and currents are inversely proportional to turns, assuming that the primary and secondary have the same number of turns and no load losses negligible. Thus, current must flow through the primary of A transformer, and will divide equally by its interconnexion on the primary, and flow in opposite directions through the two halves. The winding therefore acts as a balance coil. Since the current is in phase with the E.M.F. of transformer B, it is in quadrature with the E.M.F. of transformer A. If, however, a non-inductive load is put on transformer A when there is no load on B, a current will flow equal in both windings and in phase with the E.M.F. of the transformer. Under the assumed conditions the primary winding of transformer A acts as a balance coil for the currents in transformer B. The resultant current is as follows, made up of two components—

A. The current due to load on A equal to the secondary current, and in phase with the E.M.F. flowing in the same direction designated as 1^1.

B. The current required for B, equal to half the current in the primary of transformer B and 90° out of phase with component A, flowing in opposite direction in the two halves of the winding as 1^2, thus—

C.T.B. $= 1·15 \times$ current in its secondary of transformer B.

C.T.B.^{h} $= 0·5$ C.T.B. part of current in transformer B.

As the primaries of the two transformers have four tappings on each, numbering 1 to 8, and assuming that the two transformers are equally loaded, we get current I flowing in each secondary.

$I83 = 1·15I \quad I^2 3·1 = 1^2 3·4 = 1·15I \div 2 = 0·575I, \quad I^1 1·3$ $(= -I^1 3·1) = I^1 3·4 = I$ and since by vector addition $I^1 3·1 + 1^2 3·1$ (i.e. $\sqrt{1^2 + 0·575^2 I}$) $= I^1 3·4 + 1^2 3·4$, hence $I3·1 = I3·4 = 1·15I$. The angle between $I^1 3·1$ and $I3·1$

is 30° since its cosine is 1 ÷ 1·15 or 0·866. Hence between I8·3 and I3·1 is 120°, and similarly the angle between I8·3 and I3·4 is 120°. Therefore the three-phase currents are balanced and in phase with the generator E.M.F. The figures represent the tappings of the primaries. Several notable authorities have published further information on this subject, and it is only referred to here in conjunction with the previous statements on the subject preceding these notes, and in conjunction with the diagram published.

Some Published Troubles with Direct Current Instruments.—Very often it is found that troubles which are attributed to faulty manufacture are caused by the carelessness of other people. Some amusing instances can be recorded and some examples are given below.

In one case the ammeter on a 25 K. W. exciter had not given satisfaction, and jarring of the case was always essential until the pointer stopped dead. The scale of the meter was in amperes, but in reality the instrument was a milli-voltmeter measuring the drop across a German silver shunt, placed in series with the line whose current it was supposed to measure. Two leads joined the meter to the shunt, and these leads should have been the ones used in calibrating the scale. As this instrument operated with about 45 milli-volts a slight change in resistance would necessarily change its reading. It was found that the connexion was not making good contact, and the tightening of the contact removed the trouble. Another case where there was some trouble involved two 35·5 K.W. direct current generators in parallel driven by gas engine. One machine was all right, but the other did not act up to its demands, and when full load was reached and was so divided that each set indicated its rated load of 300 amperes, the second machine would flash over, destroying its commutation. It was discovered that the engine attached to the bad machine was barely able to carry full load, while the other was

all right. Gas engines are rated at their maximum capacity, and are not generally capable of carrying overloads. Investigation showed that the shunts of the meters which were as before described had been interchanged so that one instrument read about 18 per cent. high, the other 22 per cent. low, and in actual operation the one machine had been carrying nearly 50 per cent. more than its neighbour.

In another case where the total amperes on two outgoing feeders failed to check with the currents of the machine meters, it was found that the shunt on the feeders had been interchanged, and which when replaced indicated the correct consumption.

Gravity has an influence on the accuracy of a meter, and it is essential that these should be mounted correctly. Its effect may be noted by the trouble of a voltmeter of the type where an oil-immersed plunger is the core of a coil of wire, and the reading is the result of the plunger pull depending upon the amount of current in the coil. It was essential that the voltage was maintained close to 500 volts. The distance from the generator in the power house was a mile, so that allowing for a drop of 10 per cent. the voltage was held at 550 volts. The service became so bad that investigation was necessary. On checking the meter at the operating end it was found to be 585 volts. The voltage at the power house was 650 instead of 550 as indicated. The error was adjusted by altering the position of the meter, which had not been set up properly.

These voltmeters are generally supplied with resistances wound on pasteboard cards fitted inside the case, and in this connexion a complaint was received that a direct current voltmeter on a small exciter was reading 180 volts instead of 110 volts. It was found that the resistance had been taken out of the box at the back, and the meter was working without its resistance. The resistance was found attached to the usual pictures that adorn some such

stations. Several further instances can be recorded, but these will suffice to show how so small a matter can affect the satisfactory running of the plant, and attention is needed to the smallest.

A further case, however, is recorded below, of a lighting ammeter failing to register correctly by several hundred amperes in comparison with the other meters on the service. The meter was returned to the makers several times with no result, and the nature of complaints caused the manufacturers to send and investigate the trouble. Strays field were suggested, etc., but all to no purpose. It was found that the lighting busbar consisted of four bars + and − and equalizer the fourth bar to which the feeder breakers were connected, the other three being the bars to which the compound wound generators were connected. In the connexion between the plus bar and this fourth bar the shunt of the ammeter was connected. A new feeder had been installed to reinforce an old feeder which was connected to the plus and minus generator bars above the ammeter shunt instead of the fourth or feeder bar and the minus bar, as it should have been, therefore the meter was short circuited. When the connexions were altered the trouble disappeared. The complaint about the ammeter spread over several months, and the customer was so annoyed with the manufacturers that he closed the account. Hardly necessary to say that when he discovered the trouble was not due to the manufacturers his regrets were sincere.

Conclusion.—The author expresses regret if he has omitted any matters that would have further interested readers, endeavouring as far as possible to describe and detail such designs as are met with in standard practice, with the inclusion of the technical points of some of the plant to be controlled.

The sphere of switchgear is of a very varied nature, and any book on this subject could not cover the vast area of

design, as such is dependent upon specific conditions. It is not within the grasp of any student or engineer to efficiently deal with the subject, and the knowledge of this specialization far exceeds the knowledge required in other specialized manufacture in the production of electrical energy. Every new experience opens up another field of research, until it is found that the more information is acquired, the more information is needed, and the conclusion is forced upon one that the human element is by far the most infinite son of the industry with its failure more pronounced.

APPENDIX

ELECTRIC LIGHTING ACTS, 1882 and 1888.

BOARD OF TRADE REGULATIONS

(*A*) for securing the SAFETY of the PUBLIC and
(*B*) for ensuring a proper and sufficient SUPPLY OF ELECTRICAL ENERGY.

DEFINITIONS.

In the following regulations :—

The expression "the Undertakers" means the Undertakers for the purposes of the Order.

The expression "consumer's wires" means any electric lines on a consumer's premises which are connected with the service lines of the Undertakers at the consumer's terminals.

The expression "sub-station" means any premises in which energy is transformed or converted for the purpose of supply to consumers, and which are large enough to admit the entrance of a person after the transforming or converting apparatus is in position, provided that for the purpose of these Regulations any place within any such premises which is used solely for some purpose other than such transformation or conversion shall not be deemed to form part of a sub-station.

The expression "overhead line" means any electric line which is placed above ground and in the open air.

The expression "pressure" means the difference of electrical potential between any two conductors through which a supply of energy is given, or between any part of either conductor and the earth; and subject to the variations allowed by No. B3 of these Regulations.

(*a*) Where the conditions of the supply are such that the pressure at any pair of consumer's terminals does not exceed 250 volts the supply shall be deemed a low pressure supply.

(*b*) Where the conditions of the supply are such that the pressure exceeds 250 volts but does not exceed 650 volts the supply shall be deemed a medium pressure supply.

(*c*) Where the conditions of the supply are such that the pressure exceeds 650 volts but does not exceed 3,000 volts, the supply shall be deemed a high pressure supply ; and

(*d*) Where the conditions of the supply are such that the pressure exceeds 3,000 volts the supply shall be deemed an extra high pressure supply.

The expression "factory" has the same meaning as in the Factory and Workshop Act, 1901.

The expression "mine" means a mine to which the Coal Mines Regulations Act 1887, or the Metalliferous Mines Regulation Act 1872 applies.

Where these regulations require any metallic body to be efficiently connected with earth, it shall be connected with the general mass of earth in such manner as will ensure at all times an immediate and safe discharge of electrical energy.

Other expressions to which meanings are assigned in the Order or in the Electric Lightning Acts, 1882 and 1888, have the same respective meanings in these regulations.

A. REGULATIONS FOR SECURING THE SAFETY OF THE PUBLIC.—GENERAL.

Pressure of Supply to Consumers.

1. The pressure of a supply delivered to any consumer shall not exceed the limit of low pressure, except for special purposes, for which a medium pressure supply may be given on the consumer undertaking to comply with the following conditions :—

(*a*) Where the supply is for power purposes :—

(1) The frame of every electric motor shall be efficiently connected with earth.

(2) The consumer's wires forming the connections to motors, or otherwise in connection with the supply, shall be as far as practicable, completely enclosed in strong metal casing efficiently connected with earth, or they shall be fixed in such a manner that there shall be no danger of any shock.

(3) The supply to every motor shall be controlled by means of an efficient cut-off switch, placed in such a position as to be easily handled by the person in charge of the motor, and connected so that by its means all pressure can be cut off from the

motor itself, and from any regulating switch, resistance or other device in connection therewith.

(4) Switches, efficient fuses or other automatic circuit breakers shall be provided, so as to protect the circuits from excess of current and all switches and cutouts shall be so enclosed and protected that there shall be no danger of any shock being obtained in the ordinary handling thereof, or of any fire being caused by their normal or abnormal action.

(5) A notice shall be fixed in a conspicuous position at every motor and switch board in connection with the supply forbidding unauthorised persons to touch the motors or apparatus.

(*b*) Where the supply is for arc lamps in series.

(1) The consumer's wires forming the connections to the arc lamps, or otherwise in connection with the supply, shall be, as far as practicable, completely enclosed in strong metal casing efficiently connected with earth, or they shall be fixed in such a manner that there shall be no danger of any shock.

(2) The supply to every arc lamp shall be controlled by means of an efficient cut-off switch, placed in such a position as to be easily handled by the person in charge of the arc lighting, and connected so that by its means all pressure can be cut off from the arc lamp itself, and from any regulating switch, resistance or other device in connection therewith. Provided that where the arc lamps are connected in series across the outer conductors of a three-wire system, it shall be sufficient if one such switch be provided for each series of arc lamps.

(3) Switches, efficient fuses or other automatic cutouts shall be provided, so as to protect the circuits from excess of current, and all switches and cutouts shall be so enclosed and protected that there shall be no danger of any shock being obtained in the ordinary handling thereof, or of any fire being caused by their normal or abnormal action.

(*c*) Where the supply is for incandescent lamps in series :—

(1) The consumer's wires forming the connections to the incandescent lamps, or otherwise in connection with the supply, shall be completely enclosed in strong metal casing and this casing together with the switches and lamp holders, if metallic, shall be efficiently connected with earth.

(2) Switches, efficient fuses or other automatic cutouts shall be provided, so as to protect the circuits from excess of current, and all switches and cutouts shall be so enclosed and protected that there shall be no danger of any shock being obtained in the

ordinary handling thereof, or of any fire being caused by their normal or abnormal action.

Where the supply is for any special purpose other than those above-mentioned, or where the pressure of the supply exceeds the limits of medium pressure it shall be subject to such other regulations as the Board of Trade may from time to time prescribe.

Introduction of Three-Wire System into Consumer's Premises.

2. When the pressure between the outer conductors of a three-wire system exceeds 250 volts and the three wires of the system or two pairs of wires are brought into a consumer's premises, the supply shall be given to two pairs of terminals arranged in such a manner that there shall be no danger of any shock, and the wiring from those terminals shall be kept distinct.

Extra High Pressure Supply to Consumer's Premises.

3. An extra high pressure supply shall not be given to any consumer's premises other than a factory, a mine, or electric traction works. And no such supply shall be given except with the consent of the Board of Trade and subject to such regulations as the Board may prescribe.

Minimum Size of Conductor.

4. The sectional area of the conductor in any electric line laid or erected in any street after the date of these regulations shall not be less than that of a strand of seven wires, each of which is of No. 20 standard wire gauge, and the sectional area of every wire in a strand forming any such conductor shall not be less than that gauge.

This regulation shall not apply in the case of an electric line placed in a lamp-post.

Insulation Test of Low Pressure and Medium Pressure Mains.

5. Every low pressure and medium pressure main shall be tested for insulation after having been placed in position and before it is used for the purposes of supply, the testing pressure being the maximum pressure to which it is intended to be subjected in use, and in any case at least 200 volts, and the Undertakers shall duly record the results of the tests of each main or section of a main.

Maintenance of Insulation.

6. The insulation of every complete circuit used for the supply of energy, including all machinery, apparatus, and devices forming part of, or in connection with that circuit shall be so maintained that the leakage current shall not under any conditions exceed one-thousandth part of the maximum supply current, and suitable means shall

be provided for the indication and localisation of leakage. Every leakage shall be remedied without delay.

Every such circuit shall be tested for insulation at least once in every week, and the Undertakers shall duly record the results of the testings.

Provided that where the Board of Trade have approved of any part of any electric circuit being connected with earth the provisions of this regulation shall not apply to that circuit so long as the connection with earth exists.

Testing Insulation of all parts of High Pressure Circuit. 7. A high pressure circuit shall not be brought into use unless the insulation of every part thereof has withstood the continuous application, during half-an-hour in the case of every electric line of a pressure twice the maximum pressure to which it is intended to be subjected in use, and in the case of every machine, device, or apparatus of a pressure 50 per cent. greater than the said maximum pressure.

The Undertakers shall duly record the results of each test.

Circuit Breaker for High Pressure Mains, etc. 8. Every high pressure main, conductor, or other apparatus shall be protected by a suitable fuse or breaker,

Provided that it shall not be incumbent upon the Undertakers to provide such a fuse or circuit breaker for the outer conductor of a concentric main which is, with the approval of the Board of Trade, efficiently connected with earth.

Transformers. 9. In every case where a high pressure supply is transformed for the purpose of supply to one or more consumers, some suitable automatic and quick-acting means shall be provided to protect the consumer's wires from any accidental contact with or leakage from the high pressure system, either without or within the transforming apparatus.

Connection of Transformers with earth. 10. The metallic portion of every transformer, with the exception of the conductors thereof, shall be efficiently connected with earth.

Protection from Lightning. 11. Where any portion of any electric line or any support for an electric line is exposed in such a position as to be liable to cause injury from lightning, it shall be efficiently protected against such liability.

Report of Accidents to Board of Trade. 12. Where any accident by explosion or fire, or any other accident of such kind as to have caused or to be likely to have caused loss of life or personal injury has occurred at any part of any electric line or work, the

Undertakers shall give immediate notice thereof to the Board of Trade.

OVERHEAD LINES.

Overhead Lines. 13. Overhead lines shall not after the date of these regulations be erected or maintained except in accordance with plans approved by the Board of Trade and subject to such regulations as the Board may prescribe; provided that this regulation shall not apply to any electric lines which have been erected at the date of these regulations so long as those lines are maintained in accordance with any regulations of the Board of Trade which are in force and applicable thereto at that date and with any requirements of the Board made thereunder.

ELECTRIC LINES OTHER THAN OVERHEAD LINES.

Construction of Receptacles for Electric Lines. 14. All conduits, pipes, casings, and street boxes used as receptacles for electric lines shall be constructed of durable material, and where laid under carriage ways shall be of ample strength to prevent damage from heavy traffic, and reasonable means shall be taken by the Undertakers to prevent accumulation of gas in such receptacles.

Crossing Pipes, etc. 15. Where any electric line crosses, or is in proximity to any metallic substance, special precautions shall be taken by the Undertakers against the possibility of any electrical charging of the metallic substance from the line or from any metal conduit, pipe, or casing enclosing the line.

Continuity of Metal Conduits, Pipes and Casings of High Pressure Lines. 16. All metal conduits, pipes or casings containing any high pressure electric line shall be efficiently connected with earth, and shall be so jointed and connected across all street boxes and other openings as to make good electrical connection throughout their whole length.

Precautions to be taken when bare Conductors are Used. 17. Where the conductors of electric lines placed in any conduit are not continuously covered with insulation material they shall be secured in position, and no unfixed uninsulated material of a conducting nature shall be contained in the conduit. No such conductor shall be at a pressure exceeding 300 volts from earth.

Adequate precautions shall also be taken to ensure that no accumulation of water shall take place in any part of the con-

duit, and to prevent any dangerous access of moisture to the conductors or the insulators.

The insulators of any such electric line shall be so disposed that they can be readily inspected, but this requirement shall not apply to any such insulators which before the date of these regulations were not required by any regulation then in force to be so capable of ready inspection.

High Pressure Lines Laid Above Ground or in Subways. 18. Every portion of any high pressure electric line placed above the surface of the ground, or in any subway not in the sole occupation of the Undertakers shall be completely enclosed either in a tube of highly insulating material embedded in brickwork, masonry, or cement concrete, or in strong metal casing efficiently connected with earth.

Protection for the surface of the Ground and Electric Lines. 19. Where any high pressure electric line is laid beneath the surface of the ground, efficient means shall be taken to render it impossible that the surface of the ground or any neighbouring electric line or conductor shall become charged by leakage from the high pressure electric line.

Completion and Control of High Pressure Lines. 20. A high pressure electric line shall not be used for the supply of energy before it has been completely laid, properly jointed, examined, and tested, or until it is in the sole charge of the Undertakers, and every such line shall during its use be in the sole charge of the Undertakers.

Sub-Stations and Street Boxes.

Sub-Stations. 21. Sub-stations shall be established in suitable places and shall be in the sole occupation and charge of the Undertakers. Sub-stations shall be erected above ground wherever possible, but where necessarily underground, they shall be constructed in accordance with plans approved by the Board of Trade.

Street Boxes. 22. In addition to the provisions contained in Regulation 14 as to the construction of receptacles for electric lines, the following conditions shall be observed with respect to street boxes :—

(*a*) The covers of all street boxes shall be so secured that they cannot be opened except by means of a special appliance.

(*b*) The covers of all street boxes containing high pressure apparatus other than cables shall be connected to strips of metal

laid immediately underneath the street, and efficient means shall be taken to render it impossible that the covers or other exposed parts of these boxes, or any adjacent material forming the surface of the street, shall become electrically charged, whether by reason of leakage, defect or otherwise.

(*c*) Where street boxes are used as transformer chambers, reasonable means shall be taken to prevent as far as possible any influx of water, either from the adjacent soil or by means of pipes ; and in the case of any such street box exceeding one cubic yard in capacity ample provision shall be made, by ventilation or otherwise, for the immediate escape of any gas which may by accident have obtained access to the box, and for the prevention of danger from sparking.

(*d*) All street boxes shall be regularly inspected for the presence of gas, and if any influx or accumulation is discovered, the Undertakers shall give immediate notice to the Authority or company whose gas mains are laid in the neighbourhood of the street box.

(*e*) Where mains at different pressures pass through the same street box they shall be readily distinguishable from one another.

Maximum Power in Case of Underground Sub-Station, etc. 23. The maximum power supplied to any underground sub-station or street box shall not, without the consent of the Board of Trade, exceed 30 kilowatts in the case of a sub-station or street box containing a single transformer, or 75 kilowatts in the case of a sub-station or street box containing two or more transformers.

Consumer's Premises.

Responsibility of Undertakers for their Lines, etc., on Consumer's Premises. 24. The Undertakers shall be responsible for all electric lines, fittings, and apparatus belonging to them, or under their control, which may be upon a consumer's premises being maintained in a safe condition and in all respects fit for supplying energy.

Fire Risks. 25. In delivering the energy to a consumer's terminals the Undertakers shall exercise all due precautions so as to avoid risk of causing fire on the premises.

Main Fuses or Circuit Breakers. 26. A suitable safety fuse or other automatic circuit-breaker shall be inserted in each service line within a consumer's premises as close as possible to the point of entry, and contained within a suitable locked or sealed receptacle of fireproof construction, except in cases where

the service line is protected by fuses in a street box; but no fuse or automatic circuit breaker shall be inserted in the intermediate conductor of a three-wire system where the pressure between the adjacent conductors exceeds 125 volts.

Treatment of Service Lines and Apparatus on Consumer's Premises.

27. All service lines and apparatus placed on a consumer's premises shall be highly insulated and thoroughly protected against injury to the insulation or access of moisture, and any metal forming part of the electric circuit shall not unless efficiently connected with earth be exposed so that it can be touched. All electric lines shall be so fixed and protected as to prevent the possibility of electrical discharge to any adjacent metallic substance.

Transformers and High Pressure Apparatus to be Enclosed in Metal, etc.

28. Where the general supply of energy is a high pressure supply, and transforming apparatus is installed on a consumer's premises, the whole of the high pressure service lines, conductors and apparatus, including the transforming apparatus itself, so far as they are on the consumer's premises, shall be completely enclosed in solid walls, or in strong metal casing efficiently connected with earth and securely fastened throughout.

Connection to Consumer's Premises not to be made where Leakage would result.

29. The Undertakers shall not connect a consumer's wires with their mains unless they are reasonably satisfied that the connection would not cause a leakage from those wires or fittings exceeding one ten-thousandth part of the maximum supply current to the premises; and where the Undertakers decline to make such connection they shall serve upon the consumer a notice stating their reasons for so declining.

Discontinuance of Supply on Discovery of Leakage on Consumer's Premises.

30. If the Undertakers are reasonably satisfied, after making all proper examination by testing or otherwise, that a leakage exists at some part of a consumer's wires or fittings of such extent as to be a source of danger, any officer of the Undertakers, duly authorised by them in writing, or, if the Undertakers so require, an electric inspector, may, for the purpose of discovering whether the leakage exists at any part of a circuit within or upon any consumer's premises, by notice require the consumer at some reasonable time after the service of the notice to permit him to inspect and test the wires and fittings belonging to the consumer and forming part of the circuit.

In any case where the Undertakers require the services of an

electric inspector under this regulation they shall pay him the prescribed fee.

If on any such testing the officer or the electric inspector discovers a leakage from the consumer's wires exceeding one ten-thousandth part of the maximum supply current to the premises, or if the consumer does not give all due facilities for inspection and testing, the Undertakers shall forthwith discontinue the supply of energy to the premises in question, giving immediate notice of the discontinuance to the consumer, and shall not recommence the supply until they are reasonably satisfied that the leakage has been removed. This regulation shall not affect any power contained in the Order or otherwise enabling the Undertakers to discontinue the supply.

Appeal to Electric Inspector. 31. If any consumer is dissatisfied with the action of the Undertakers in refusing to give, or in discontinuing or in not recommencing the supply of energy to his premises, the wires and fittings of that consumer shall, on his application and on payment of the prescribed fee, be tested for the existence of leakage by an electric inspector.

This regulation shall be endorsed on every notice given under the provisions of either of the two last preceding regulations.

Arc Lighting.

Height from Ground. 32. Arc lamps used in any street for public lighting shall be so fixed as not to be in any part at a less height than 10 feet from the ground.

Arc Lamps to be Guarded. 33. All arc lamps shall be so guarded as to prevent pieces of ignited carbon or broken glass falling from them, and shall not be used in situations where there is any danger of the presence of explosive dust or gas.

Connection of Circuits with Earth.

Connection with Earth of a Three-Wire System. 34. Where the pressure of a supply between the adjacent conductors of a three-wire system of mains exceeds 125 volts the intermediate conductor shall be connected with earth, subject to the concurrence of the Postmaster-General, and in accordance with the following conditions :—

(*a*) The connection with earth of the intermediate conductor shall be made at one point only on each distinct circuit, namely, at the generating station, sub-station, or transformer, and the

insulation of the circuit shall be efficiently maintained at all other parts.

(*b*) The current from the intermediate conductor to earth shall be continuously recorded, and if it at any time exceed one-thousandth part of the maximum supply current steps shall be immediately taken to improve the insulation of the system.

PENALTIES.

Penalties for Default. 35. If the Undertakers make default in complying with any of the preceding regulations, they shall on conviction be liable to a penalty not exceeding £10 for every such default, and to a daily penalty not exceeding £10. The recovery of a penalty under these regulations shall not affect the liability of the Undertakers to make compensation in respect of any damage or injury which may be caused by reason of the default.

B. REGULATIONS FOR ENSURING A PROPER AND SUFFICIENT SUPPLY OF ELECTRICAL ENERGY.

Undertakers to Provide Constant Supply. 1. From the time when the Undertakers commence to supply energy through any distributing main, they shall maintain a supply sufficient for the use of all the consumers for the time being entitled to be supplied from that main, and that supply shall, except so far as may be otherwise agreed upon from time to time between the local authority and the Undertakers be constantly maintained, and in the case of continuous currents, without change of polarity. Provided that, for the purpose of testing, or for any other purposes connected with the efficient working of the undertaking, the authority by whom the electric inspector is appointed may give permission to the Undertakers to discontinue the supply at such intervals of time and for such periods as that authority may think expedient. When the supply is so discontinued, or the polarity is changed, notice to all persons likely to be affected shall be given of such discontinuance, or change, and of the probable duration thereof.

Measures for Restricting Area Liable to Stoppage. 2. The system of distributing mains shall be separated into sections corresponding approximately to the different feeders, and these sections shall be interconnected only through suitable circuit-breakers or fuses, arranged so as to be easily inspected.

Fixing of System and Declared Frequency. 3. Before commencing to give a supply of energy to any consumer, the Undertakers shall declare to that consumer the system which they propose to adopt, whether alternating or continuous current, and, in the case of alternating current, the frequency, that is to say, the number of complete periods per second at which they propose to supply. The system and frequency so declared shall be maintained subject, as respects frequency, to a variation not exceeding $2\frac{1}{2}$ per cent. from the declared frequency and shall not be altered or departed from except by consent of the local authority, and upon such terms and conditions as the local authority may impose, and after public notice has been given during a period of one month, in such manner as the local authority may require, of the intention of the Undertakers to apply for consent to alter the same. If the local authority refuse to consent to an alteration or impose any terms or conditions with which the Undertakers are dissatisfied, the Undertakers may appeal to the Board of Trade, whose decision shall be final.

Penalty for Default. 4. If the Undertakers make default in complying with any of these regulations as to supply, they shall, subject to the provisions of the Order, be liable on conviction to a penalty not exceeding £1 for every such default, and to a daily penalty not exceeding £1.

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